JOURNAL OF THE ROYAL SOCIETY OF WESTERN AUSTRALIA

VOLUME 73 (PART 1)

CONTENTS VOLUME 73 PART 1 1990

Page

The geomorphology and soils of the Yoongarillup Plain in the Mandurah-Bunbury coastal zone, South-western Australia: a critical appraisal **V Semeniuk** 1

The coastal landforms and peripheral wetlands of the Peel-Harvey estuarine system **C A Semeniuk & V Semeniuk** 9

Youndegin meteorite shower: a re-assessment of provenance **W H Cleverly & E I Cleverly** 23

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VOLUME 73 (PART 2)

JOURNAL OF THE ROYAL SOCIETY OF WESTERN AUSTRALIA

CONTENTS VOLUME 73 PART 2 1990

	Page
Limnology of the southern acid peat flats, South-western Australia **B J Pusey & D H Edward**	29
Bioerosion, notch formation and micromorphology in the intertidal and supratidal zones of a calcareous sandstone stack **M Abensperg-Traun, G A Wheaton & I G Eliot**	47
Distribution, habitat and behavioural patterns of *Nickerlea sloanei* (Lea) (Coleoptera: Cincindelinae) in Southwestern Australia **G P Hall & G R Friend**	57

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JOURNAL OF THE ROYAL SOCIETY OF WESTERN AUSTRALIA

CONTENTS VOLUME 73 PART 3 1991

Page

Radiocarbon ages of some coastal landforms in the Peel-Harvey estuary, south-western Australia **V Semeniuk & C A Semeniuk** 61

The epizoic diatom *Falcula hyalina* Takano on a pelagic copepod from the Swan River estuary, Western Australia **Jacob John** 73

The early evolution of the plant life of south-western Australia: comment **G J Retallack**; reply **J S Beard** 77

The ants of a vine thicket near Broome: a comparison with the northwest Kimberley **Alan N Anderson & Allan H Burbidge** 79

Australites from four localities in the Eastern Goldfields, Western Australia **W H Cleverly** 83

Contents Volume 71 89

Contents Volume 72 93

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VOLUME 73 (PART 4)

CONTENTS VOLUME 73 PART 4 1991

Page

Distribution of diatoms in the northern Kimberley region, Western Australia in relation to water chemistry **E R Tudor, Dean W Blinn & David M Churchill** 93

A new reference section for the Toolonga Calcilutite, Carnarvon Basin, Western Australia **David Lynch** 101

New data on the Permian crinoid family Calceolispongiidae in Western Australia **Curt Teichert** 113

An account of the decline of Lake Towerrinning, a wheatbelt wetland **R H Froend & A J McComb** 123

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The geomorphology and soils of the Yoongarillup Plain in the Mandurah—Bunbury coastal zone, South-western Australia: a critical appraisal

V Semeniuk

21 Glenmere Rd, Warwick, WA 6024

Manuscript received December 1988, accepted July 1989

Abstract

The term Yoongarillup Plain, and a suite of associated landform-soil units, to date, have been inconsistently applied to landform units and inaccurately mapped on the Swan Coastal Plain in the Mandurah to Bunbury area of SW Australia. The term Yoongarillup Plain should be applied, geomorphologically, in a more restricted sense to refer to the plain between Mandurah and Bunbury that is underlain by fossiliferous limestone mantled by a variable but relatively thin blanket of quartz sand. The term should not be applied to the low undulating terrains and plains developed within the Quindalup Dunes, or to shoreline landforms of the Peel-Harvey system developed by estuarine processes. With regard to the soil groups, it is suggested that the term Yoongarillup Association be applied to surficial materials of the Yoongarillup Plain as defined in this paper, and that the materials underlying the Quindalup Dunes, the estuarine fringes, and the other plain geomorphic units of Holocene age in the region be excluded from the Yoongarillup Association.

Introduction

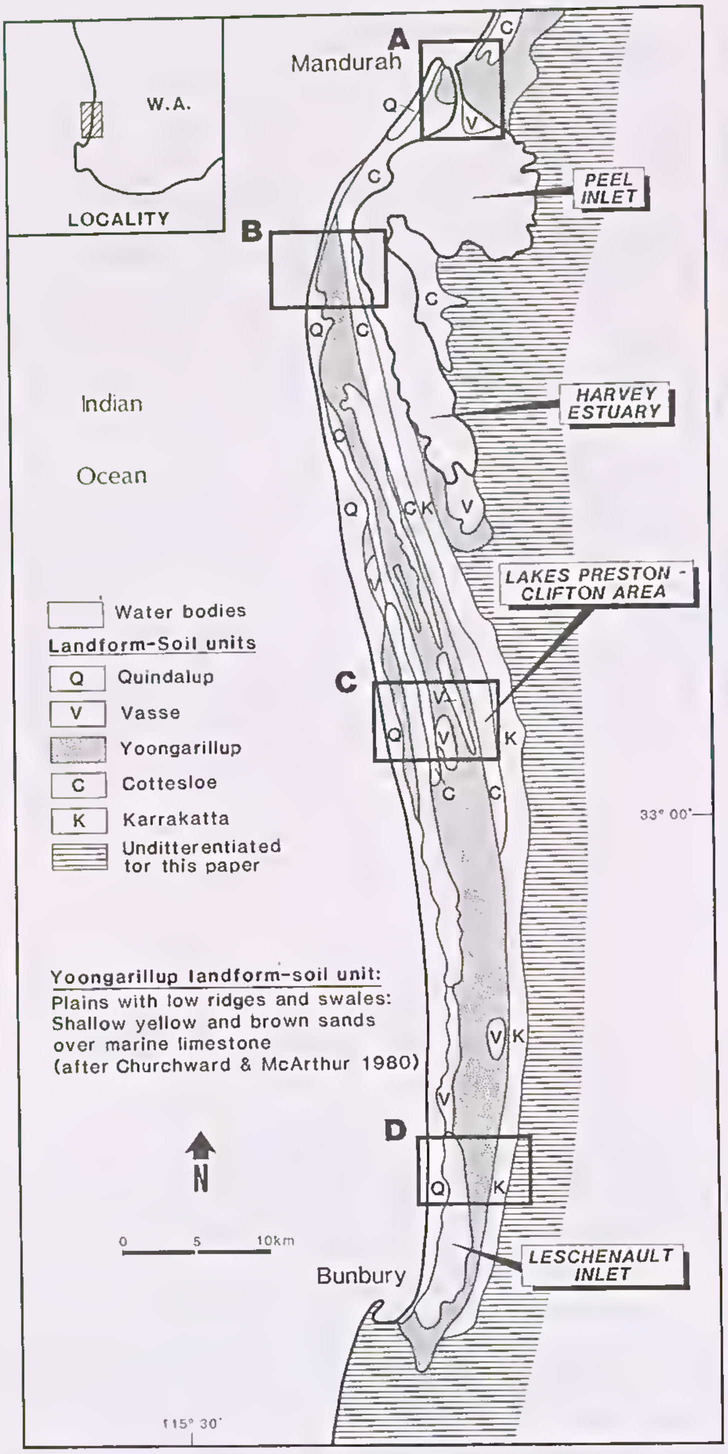
A geomorphic unit (the Yoongarillup Plain) and a suite of associated landform-soil units form part of the Swan Coastal Plain in the Mandurah to Bunbury area of SW Australia (Churchward & McArthur 1980, McArthur & Bartle 1980). Information on the Yoongarillup Plain, and the landform-soil subdivisions within it, subsequently has been used to outline land use potential and vegetation habitats/associations, and to delineate areas for conservation (McArthur & Bartle 1980, Churchward & McArthur 1980, Heddle *et al* 1980, Trudgen 1984). It also can be anticipated that the definition, distribution and relationships of the Yoongarillup landform and soil units may be used to resolve the Quaternary history of the Swan Coastal Plain in this region.

Data from recent investigations (Semeniuk 1990), however, are incompatible with the descriptions and mapped distribution of the Yoongarillup landform and soil units of McArthur & Bartle (1980), and hence there is a need for discussion and some reconciliation of the varying data. These issues are important because the present description and definition of the Yoongarillup landforms and soils in the literature are misleading, and may result firstly in incorrect interpretations of the Quaternary evolution of the Swan Coastal Plain, and secondly to inappropriate decisions on land use potential and conservation in this region. For instance, the current definition of Yoongarillup Plain by McArthur & Bartle (1980) and Churchward & McArthur (1980) actually encompasses a variety of different landform units, and is more complex than presently indicated, and thus the real diversity of the terrain is not fully appreciated. This aspect would be important in the assessment of conservation potential of any landform units within the Yoongarillup Plain in the region.

The objectives of this paper therefore are: 1) to provide a brief review of the definitions and concepts of Yoongarillup landforms and soils; 2) to provide field information to compare with these current definitions; 3) to discuss any differences in order to constructively clarify the definition of the Yoongarillup landform and soils so that the units may be of practical and scientific use to later workers; and 4) to suggest aspects that require further research or clarification. The data for this paper are based on the published literature on the Leschenault Peninsula area (Semeniuk & Meagher 1981a, Semeniuk 1985), information on calcrete in the region (Semeniuk & Meagher 1981b, Semeniuk & Searle 1985a, Semeniuk 1986), a description of coastal landforms in the Peel-Harvey estuary (Semeniuk & Semeniuk 1989a), fieldwork, and various drilling programs undertaken in the region using a reverse air circulating coring device. The drilling program culminated in some 250 cores, to depths of 30 m, the data from some of which are presented here. Locations of drill sites are presented in Semeniuk (1983, 1985, 1990), C A Semeniuk (1988), and Semeniuk & Semeniuk (1990).

Previous work

The term "Yoongarillup" appears first to have been used by McArthur & Bettenay (1958) to refer to Yoongarillup Sand, a sand unit which they assumed to be a surficial soil, overlying fossiliferous limestone in the


W.A.
LOCALITY
A
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Mandurah
PEEL INLET
HARVEY ESTUARY
LAKES PRESTON - CLIFTON AREA
LESCHENAULT INLET
Bunbury
Indian
Ocean
Water bodies
Landform-Soil units
Q Quindalup
V Vasse
Yoongarillup
C Cottesloe
K Karrakatta
Unditterentiated tor this paper
Yoongarillup landform-soil unit:
Plains with low ridges and swales:
Shallow yellow and brown sands over marine limestone
(after Churchward & McArthur 1980)
N
0 5 10km
33° 00'
115° 30'
Q
V
C
K

Figure 1 Location of study area, distribution of the Yoongarillup Plain after Churchward & McArthur (1980), and location of selected small study areas shown in Figure 2.

Busselton area. Later, Bettenay *et al* (1960) used the term Yoongarillup Association to refer to soils and surficial materials overlying fossiliferous limestone occurring in the areas south of Bunbury. Thus in the areas south of Bunbury, because it was overlying fossiliferous limestone instead of aeolian limestone, the Yoongarillup Association replaced (and by implication, was equivalent to) the Cottlesloe Association of the Swan Coastal Plain north of Bunbury. At this stage the term Yoongarillup appeared to be confined to the region south of Bunbury. Churchward & McArthur (1980) used the term Yoongarillup unit, as a landform-soil unit, to denote the plains between Mandurah and Bunbury underlain by marine limestone, thus extending the original term to areas north of Bunbury (Fig. 1). Churchward & McArthur (1980) also noted that estuarine deposits, referred to the Vasse unit, could be clearly separated from Yoongarillup units in this region

McArthur & Bartle (1980), in an investigation of the terrain between Mandurah and Bunbury, used the term Yoongarillup to refer to the soils and landforms in this region. But the term now was used in a geomorphic sense (*ie* Yoongarillup Plain) to refer to the relatively flat low-lying terrain, or plain, underlain by fossiliferous limestone on the western part of the Swan Coastal Plain. and in a soil sense (encompassing various soils and surfical units notated by alphabetic abbreviations) to refer to the suite of soils and surficial materials on this plain The definitions of the Yoongarillup Plain and its associated suite of soil units as described by McArthur & Bartle (1980) are presented below, because it is important to compare these definitions and the areas mapped by McArthur & Bartle (1980) with descriptions of materials actually occurring in the study area.

According to McArthur & Bartle (1980), the Yoongarillup Plain (geomorphic definition) is a flat terrain with minor ridges and swales; there are depressions with swamps and lakes, and the terrain is underlain by marine fossiliferous limestone, with a capping of secondary calcite, overlain by siliceous sand. The landform-soil units of McArthur & Bartle (1980) are:

Ys	grey sandy surface, a light grey subsoil, and a thin layer of yellow sand resting directly on limestone at 30-40 cm.
Yls	bare limestone.
Yb	swamps in depressions, often drained; dark brown loam over a layer of calcareous marl which then passes into shell beds.
Ysp	stony plains in slight depressions; black loam over limestone; much outcrop and loose rock
Pg	upper terraces fringing lakes; grey siliceous sand, with a thin layer of yellow sand resting directly on soft fossiliferous limestone at 20-30 cm.
Ps	lower terrace fringing lakes; black loam overlying marl or shell beds at about 30 cm.
Pr	benches fringing Peel Inlet and Harvey Estuary; includes saline flats, sandy terraces, and sandy beach ridges.

The Yoongarillup Plain as a geomorphic unit

As presently defined and shown on maps (Churchward & McArthur 1980, McArthur & Bartle 1980), the Yoongarillup Plain appears to encompass several geomorphic units underlain by various stratigraphic sequences. These units, their stratigraphic sequences, and the study sites of this paper are (Fig. 2, Table 1):

1) an extensive, shore-parallel tract of relatively low-lying terrain underlain by fossiliferous limestone with negligible cover of quartz sand (site 6, Fig. 2B);

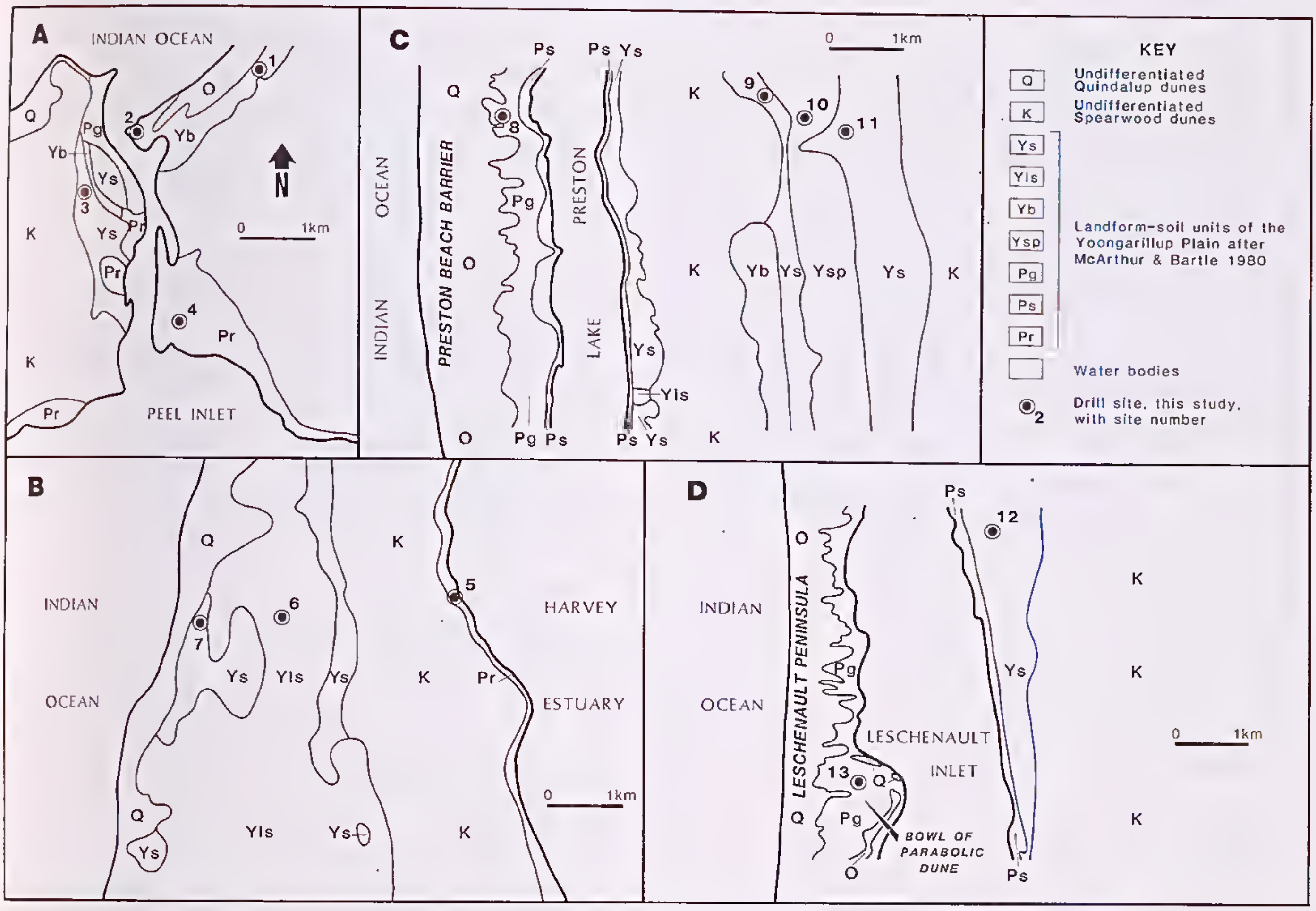

Figure 2 A, B, C, & D: Distribution of landform-soil units drawn from McArthur & Bartle (1980) in the selected small study areas, and location of drill sites 1-13 of this study. Key to landform-soil units of McArthur & Bartle (1980) is listed in text. Description of drill sites presented in Table 1.

2) an extensive, shore-parallel tract of relatively low-lying terrain underlain by fossiliferous limestone with variable cover of yellow, brown to grey quartz sand (sites 7 & 12, Fig. 2B,D);

3) plains underlain by quartz sand, with no underlying fossiliferous marine limestone (site 9 & 11, Fig. 2C);

4) wetlands (damplands, sumplands and lakes, using the terminology of C A Semeniuk, 1987), with various types of sedimentary fill of various ages (site 10, Fig. 2C);

5) coastal beachridge ribbons overlying riverine sand deposits (site 2, Fig. 2A);

6) geomorphically degraded terrain of Quindalup Dunes in the Leschenault Peninsula area (site 13 on Fig. 2D) referred to as the woodland plain (Semeniuk & Meagher 1981a), and equivalent geomorphic units on the Leschenault-Preston barrier (Searle & Semeniuk 1985) in the Preston Beach area (site 8, Fig. 2C); and

7) various types of estuarine Holocene shoreline terraces and flats (Semeniuk & Semeniuk 1990) in the Peel-Harvey system (sites 1, 3, 4 & 5, Fig. 2A,B).

The Yoongarillup Plain could be viewed as polygenetic in origin. However, it is more likely that the term has been applied to landform units inconsistently (Table 1). That is, some of the landform components of the Yoongarillup Plain described by McArthur & Bartle (1980) belong to previously defined and accepted landform-soil units. For instance, the Quindalup Dunes along the full length of the Leschenault-Preston barrier consist of landforms that range from active, mobile, unvegetated dunes, to high-relief dunes fixed by vegetation, to degraded, fixed dunes, which grade to a plain. This is apparent firstly in the differentiation of the Quindalup Dunes by McArthur & Bartle (1980) into units of Q1, Q2, Q3, and Q4, and secondly in the recognition by Semeniuk & Meagher (1981a) that the woodland plain is the end product of dune terrain degradation. All these Quindalup landform units are inter-gradational, and are underlain by the same stratigraphy—the Safety Bay Sand with thin calcrete sheets and buried soils, and the estuarine Leschenault Formation (Semeniuk 1983, 1985). Use of the term Yoongarillup Plain by McArthur & Bartle (1980) on the Leschenault Peninsula and on the barrier in the Preston Beach area therefore allocates a degraded Holocene Quindalup Dune terrain to a geomorphic unit defined to be a plain underlain by very shallowly buried Pleistocene limestone.

Table 1

Description of landforms and stratigraphy at the study sites, and correlation with units of McArthur and Bartle (1980)

Study site (locations shown on Fig. 2)	Units of McArthur and Bartle (1980)	Landform description (this paper)	Stratigraphy[1] (this paper)	Comments
1	Yb	Linear lowland (wetland)	Mud and shelly mud 3 m thick, overlying limestone	Stranded estuarine embayment
2	Yb	Low coastal beachridge plain	Dune sand (Safety Bay Sand) 1-2 m thick overlying Becher Sand, overlying coarse, gravelly quartz sand	Holocene coastal dune deposits overlying seagrass deposits and river sediments
3	Ys	Low plain of sand ridges and hummocks and intervening depressions fringing the estuary	Sand and shelly sand overlying estuarine deposits 4-20 m thick, and an irregular basement of limestone at depth which locally crops out; thin calcrete sheet within 1 m of surface	Stranded channel shoal complex formed during a higher Holocene sealevel
4	Pr	Extensive flat fringing the estuary	Shelly sand and mud, 1-4 m deep, overlying an irregular basement of limestone, which locally crops out	Relict tidal delta complex formed during a higher Holocene sealevel; Churchward and McArthur refer this unit to the Vasse, while McArthur and Bartle refer it to Pg of the Yoogarillup Plain
5	Pg	Narrow platform fringing the estuary	Veneer of mud and muddy sand overlying several metres of sand; aeolian limestone at depth	Shore-fringing marginal platform
6	Yls	Undulating stony plain with parallel low ridges and swales	Veneer of humic and yellow quartz sand on aeolian limestone 1-4 m thick overlying marine limestone	Nearly conforms to the definition of Yls except that surficial sand overlies aeolian limestone
7	Ys	Low sandy plain	Humic soil veneer overlying grey sand 1 m thick overlying marine limestone	Conforms to definition of Ys
8	Pg	Low undulating sandy plain	Dune sand (Safety Bay Sand) (1-8 m thick) overlying Becher Sand; calcrete 0.3 m thick, within 1 m of surface; thick humic soil at surface;limestone at 20-30 m	Degraded Holocene dunes of the Leschenault-Preston barrier overlying seagrass deposits
9	Ys	Low sandy plain	Quartz sand to 8-12 m; thin humic soil at surface	Part of a quartz sand sheet, buried by limestone on its western margin
10	Ysp	Wetland	Carbonate mud 3 m thick overlying indurated carbonate mud and soft carbonate mud to 6 m, which rests on limestone; surface mud locally calcretised to 10-20 cm	Wetland fill deposits
11	Ys	Stony plain	Humic soil 0.5 m thick overlying shelly marine limestone	Conforms to definition of Ys
12	Ys	Low sandy plain	Thin humic soil on yellow sand 1-2 m thick, overlying shelly marine limestone; limestone crops out at estuary shore where yellow sand cover has been stripped	More or less conforms to definition of Ys
13	Pg	Low undulating sandy plain	Thick humic soil overlying dune sand (1-5 m thick), overlying estuarine Leschenault Formation; thin calcrete sheet locally within 1 m of surface	Degraded Holocene dunes of Leschenault Peninsula barrier overlying estuarine deposits

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[1] Formal stratigraphic nomenclature of units from Semeniuk (1983) and Semeniuk and Searle (1985b).

Similarly with the shoreline types in the Peel-Harvey estuary—much of the flat to plain estuary-fringing landforms have formed by late Holocene estuarine processes (Semeniuk & Semeniuk 1990) and should not be linked to landforms largely formed during the Pleistocene by coastal marine sedimentation and subsequent subaerial processes. This is particularly relevant when the estuarine plain landforms are not even connected or directly attached to the Pleistocene plain. That is, they cannot be directly traced into the Pleistocene unit, since there is an intervening high-relief ridge of the Spearwood Dunes separating the Pleistocene plain and the Holocene estuarine flats. Thus, again, use of the term Yoongarillup Plain by McArthur & Bartle (1980) on the margins of the Peel-Harvey estuary allocates Holocene landforms to a geomorphic unit defined as a plain underlain by very shallowly buried Pleistocene limestone. The same rationale applies to the other Holocene landforms which are flat, or undulating, or plains, that have been allocated to the system of the Yoongarillup Plain—they should not be considered as part of the Yoongarillup Plain.

The soils of the Yoongarillup Plain

There are two aspects that need to be addressed with regards to the soils of the Yoongarillup Plain—firstly the meaning and use of the term "association", and how it is applied to the surficial materials of this plain, and secondly, the validity and accuracy of the definitions and mapped distribution of the soils defined by McArthur & Bartle (1980).

Soils of the Yoongarillup Plain originally were defined to be an association by Churchward & McArthur (1980). An association consists of two or more soils occurring together in a characteristic pattern in a given geographic area; the soils should be distinguishable from each other, but on all except detailed soil maps, they should be grouped together because of their intricate areal distributions (Bates & Jackson 1987). On the other hand, Conacher & Dalrymple (1977) discuss in some detail the various uses and meanings of the term "soil association", noting that the soil-association concept has become the practical topographical mapping tool if only because uniformity of parent material is demanded. On these bases the soils of the Yoongarillup Association as described by McArthur & Bartle (1980) are not justified to be included into an encompassing group such as a soil association. The surficial materials referred to as soils are readily mapped as separate units. In addition, it should be noted that the soils are developed on markedly different physical and genetic geologic units, *ie* they have markedly different parent materials which are of diverse ages ranging from at least two stages of the Pleistocene to the middle and late Holocene (Table 1).

With regard to the accuracy of the mapping of the soils of the Yoongarillup Plain, it is evident that the soils as defined are incorrectly mapped or mis-identified in many situations. McArthur & Bartle (1980) do not provide a data base or location of sampling sites, and so it is difficult for subsequent investigators to revisit localities to resample, re-interpret, compare results, or propose alternative working hypotheses. It is not clear therefore whether their maps are based on a few soil sampling sites supplemented by aerial-photograph interpretation, or numerous systematically spaced field sample sites within each of the mapped units. Reliability diagrams also are not provided. Consequently, in order to compare the results and hypotheses of McArthur & Bartle (1980) with those of subsequent studies (*eg* Semeniuk 1990), it is necessary to select a portion of the terrain mapped by McArthur & Bartle (1980) and ground truth their terrain and soil designations. Therefore, four such small selected areas of landform-soil units drawn from the maps of McArthur & Bartle (1980), upon which are located the drill sites used in this study, are presented in Fig. 2.

Ideally, the map units and descriptions of McArthur & Bartle (1980) should be comparable with the descriptions of subsequent investigators. Information on the setting and stratigraphy of the various drill sites located in the various landform-soil units of McArthur & Bartle (1980) are presented in Table 1. It is evident that some of the drill site results either conform with the designated soil type for that locality (*eg* site 11), or are different from the stratigraphy and soils expected at the locality, but are not that markedly different to warrant wholesale exclusion from that nominated soil (*eg* site 12, which actually has 1-2 m rather than 0.3-0.4 m of quartz sand overlying fossiliferous limestone). However, the results from the remaining sites are markedly different from the landform-soil types that are designated for those sites (*eg* the landform-soil unit Ys at site 9, and the shallow stratigraphy of unit Pg at Leschenault Peninsula (site 13), the Leschenault-Preston barrier at Preston Beach (site 8), and along the Peel Inlet exchange channel at Mandurah (site 3).

It appears that a thin sheet of calcrete occurring at shallow depth at sites 3, 8 & 13 (Semeniuk & Meagher 1981b, Semeniuk & Searle 1983, and Semeniuk 1986) was interpreted by McArthur & Bartle (1980) to be Pleistocene limestone. This sheet of calcrete in the near-estuarine locations is developed on shell-bearing estuarine deposits formed at higher Holocene sealevel stands (Semeniuk & Semeniuk 1990), and therefore has shell incorporated into the calcrete, thus adding to the confusion between calcrete impregnated shelly Holocene sand and genuine shelly Pleistocene limestone. However, petrographic evidence in the calcretes, the full stratigraphic sequence above and below the calcrete, and radiocarbon ages demonstrate that the calcrete overprints and indurates Holocene deposits (Semeniuk & Semeniuk 1990). Holocene calcrete should not be confused with Pleistocene limestone.

Discussion

Comparison of data presented here with the work of McArthur & Bartle (1980) indicates that soil groups as defined within the Yoongarillup unit have been misapplied, and inaccurately mapped. These discrepancies lead to a number of conclusions and recommendations. Firstly, the term Yoongarillup Plain as a geomorphic entity should not be applied to incorporate all plains and flats in the Mandurah to Bunbury area. Rather, the term should be applied in a more restricted sense to refer to *the plain, with accompanying Pleistocene beachridge lines, between Mandurah and the northern part of Leschenault Inlet that is underlain by fossiliferous limestone mantled by a variable but relatively thin blanket of quartz sand.* In this context, the term is coincident with a fossil (Pleistocene), prograded beachridge plain that formed in a geographically restricted area between Mandurah and Bunbury behind a barrier limestone island chain as described by Semeniuk (1990). The topography, stratigraphy and sedimentological setting of the Pleistocene plain was similar to the Holocene Rockingham-Becher Plain as described by Searle *et al* (1988).

The term *Yoongarillup Plain* should not be applied to the low undulating terrains and plains developed within the Quindalup Dunes, or to shoreline landforms of the Peel-Harvey system developed by estuarine processes. A new term for the estuarine geomorphic systems is warranted; I suggest that the term *Vasse Estuarine System* be used (not Vasse Estuarine and Lagoonal System, as suggested by Wells and Hesp, undated). With regard to the wetlands, it is arguable whether they should be regarded as part of the Yoongarillup Plain in its suggested re-definition above, or as separate geomorphic units. It may be preferable to leave the wetlands as part of an assemblage of terrain types within the Yoongarillup Plain, because in reality some are a system of depressions within the plain, but final resolution of this matter must await future work.

With regard to the soil groups, I suggest that the term *Yoongarillup Association* be applied to surficial materials underlying the Yoongarillup Plain as defined in this paper, and that the surficial materials underlying the Quindalup Dunes, the estuarine fringes, and the other geomorphic units in the region be excluded from the Yoongarillup Association. The surficial materials bordering the Peel-Harvey estuary are more aptly incorporated into the Vasse unit of Churchward & McArthur (1980), and those occurring in the Quindalup system are more aptly referred to the Quindalup Association. Finally, I suggest that a rigorous re-mapping of soil association units be undertaken in the Mandurah-Bunbury area. However, in the future, before landform-soil units are erected and mapped, attention should be paid to features such as calcretes and humic soils, the separation of primary and secondary features in the surficial materials, the lithostratigraphic sequence as the basis of identifying parent materials for soils, the age structure of stratigraphic sequences underlying the various landforms, and the evolutionary processes leading to the development of the various landforms and soils.

Some of the mapping suggested above has already commenced (*cf* Gozzard 1987; Wells & Hesp, undated). Gozzard (1987) has carried out mapping of geomorphic units (landform units) in parts of this region. Gozzard (1987) clearly separates the Yoongarillup Plain unit from the Spearwood Dunes and estuarine units, and also differentiates the various geomorphic components (such as dune ridge lines) within the Yoongarillup Plain.

Wells and Hesp (undated), however, in their mapping of landform and soil units, have abandoned the term Yoongarillup Plain, and refer to the low-lying plain area of fossiliferous limestone in the region as "Spearwood Dune and Plain System"—a procedure I do not support, in that it aggregates a plain unit with a dune unit only because they both are underlain by Pleistocene limestone. The term Spearwood Dune should be applied to terrain comprised of Pleistocene dunes (aeolianite) that are similar to those in the coastal region of Perth, and not to a time-rock unit, or to a formational unit. The plain between Mandurah and Bunbury is not similar to the terrain of the Spearwood Dunes as evident in the type area of Spearwood, and the allocation of this plain to the Spearwood Dunes and the subsequent re-definition of the Spearwood Dunes to incorporate limestone plains is unacceptable. To adequately differentiate the markedly different geomorphic entities on the Swan Coastal Plain, for purposes of landform mapping and for unravelling the Quaternary history, the Yoongarillup Plain needs to be separated from the Spearwood Dunes.

Other aspects of the mapping by Wells and Hesp (undated) similarly are problematical. While they separate the limestone plain from the estuarine units, they aggregate these estuarine units with wetland/lagoonal/lacustrine units, and river units. Estuarine units should be separated from the wetland/lagoonal/lacustrine units. The riverine units are normally referred to the Pinjarra Plain, but these authors do not use the term Pinjarra Plain for riverine flats and plains that are proximal to the Peel-Harvey estuary. Many of the map units of Wells and Hesp (undated) also are incompatible with the drilling results of Semeniuk & Semeniuk (1990), and the drill data presented by Gozzard (1987). For instance, the map units V1 and V6 along the northern edge of Peel Inlet is inconsistent with aerial photograph information and the mapping and drilling results of Semeniuk & Semeniuk (1990). Finally, there is no reliability diagram, or map of sampling sites provided by Wells and Hesp (undated), to assess the reliability of their map units.

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The coastal landforms and peripheral wetlands of the Peel-Harvey estuarine system

C A Semeniuk[1] & V Semeniuk[1]

21 Glenmere Road, Warwick, WA 6024

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Abstract

Numerous, varied physical (hydrodynamic, sedimentologic and geomorphic) processes interact to determine the type, location, configuration, extent and evolution of the shore and the peripheral wetlands of the Peel-Harvey system. Twelve types of shore are identified in the estuarine system: tidal shoals, active tidal delta, stranded channel shoal complex, relict tidal delta, stranded estuarine embayment, spit-lagoon complexes, beachridge complexes, marginal platforms, erosional sandy shore, limestone cliff—pocket beach shore, lobate fluvial delta complex, and elongate fluvial delta complex. Ten of these shore types wholly or partly contain wetlands.

Introduction

The Peel-Harvey estuarine system has been studied from physical, chemical, biological and geological viewpoints, as summarised by Hodgkin *et al* (1980). This estuarine system is now regarded to be of undoubted regional to national significance because of its natural history features, the wealth of avifauna that utilize the area, and the case study of eutrophication that it presents. Significantly, also, large tracts of estuarine shores have been reserved for flora and fauna in recognition of the role of foreshores in fauna conservation.

Most of the work on the Peel-Harvey estuarine system to date has concentrated on subdivision of the sublittoral zone. For instance, Brown *et al* (1980) subdivide the system (with formal geographic nomenclature) into components of basins, shelves, sills and deltas. However, the shore types of the estuarine system, encompassing the supralittoral and littoral zones, to date have not been extensively described and classified, particularly from the point of view of development of peripheral wetlands. The objective of this paper is to provide such a description: so that the physical basis for development of peripheral wetland habitats and their flora can be appreciated; so that representative but as yet unsecured tracts of shoreline can be highlighted for potential conservation; and so that the information may provide a framework for later more detailed studies. The approach adopted here in subdividing a large estuary into various shore types can be applied to other estuaries in Western Australia and elsewhere in Australia to provide a basis for differentiating types of peripheral wetlands, and for determining whether there is adequate variety of shore and wetland types secured in reserves.

Materials & methods

This study is based on ground surveys to map the terrain and vegetation units, transects through representative areas (Fig. 1), and interpretation of aerial photographs. The entire shoreline of the Peel-Harvey estuary was surveyed and classified either by boat or by land access. Detailed transect surveys involved: topographic levelling relative to AHD; soil sampling; augering and trenching to 1 to 4m to determine stratigraphy; groundwater sampling; and describing floristics and structure of the vegetation. Selected localities also were cored to 30m using a reverse air circulation corer (Fig. 1). The structure, fabric, texture and composition of soil and stratigraphic samples were described in the laboratory to define the lithologic suites.

Regional setting & coastal processes

The geomorphic setting, climate, hydrology, hydrodynamics and sedimentologic processes of the estuarine system are described briefly below as background for this paper. More detailed information on some of these physical features for this area is presented in Hodgkin *et al* (1980), Black & Rosher (1980) and Brown *et al* (1980). The sedimentological processes operating in the Peel-Harvey system are largely undescribed in the literature.

Geomorphic setting

The Peel-Harvey estuary is a compound type barred by a Pleistocene barrier, and essentially is three coalesced estuary systems; its connexion with the sea is mostly choked by an emergent (stranded) tidal delta and channel

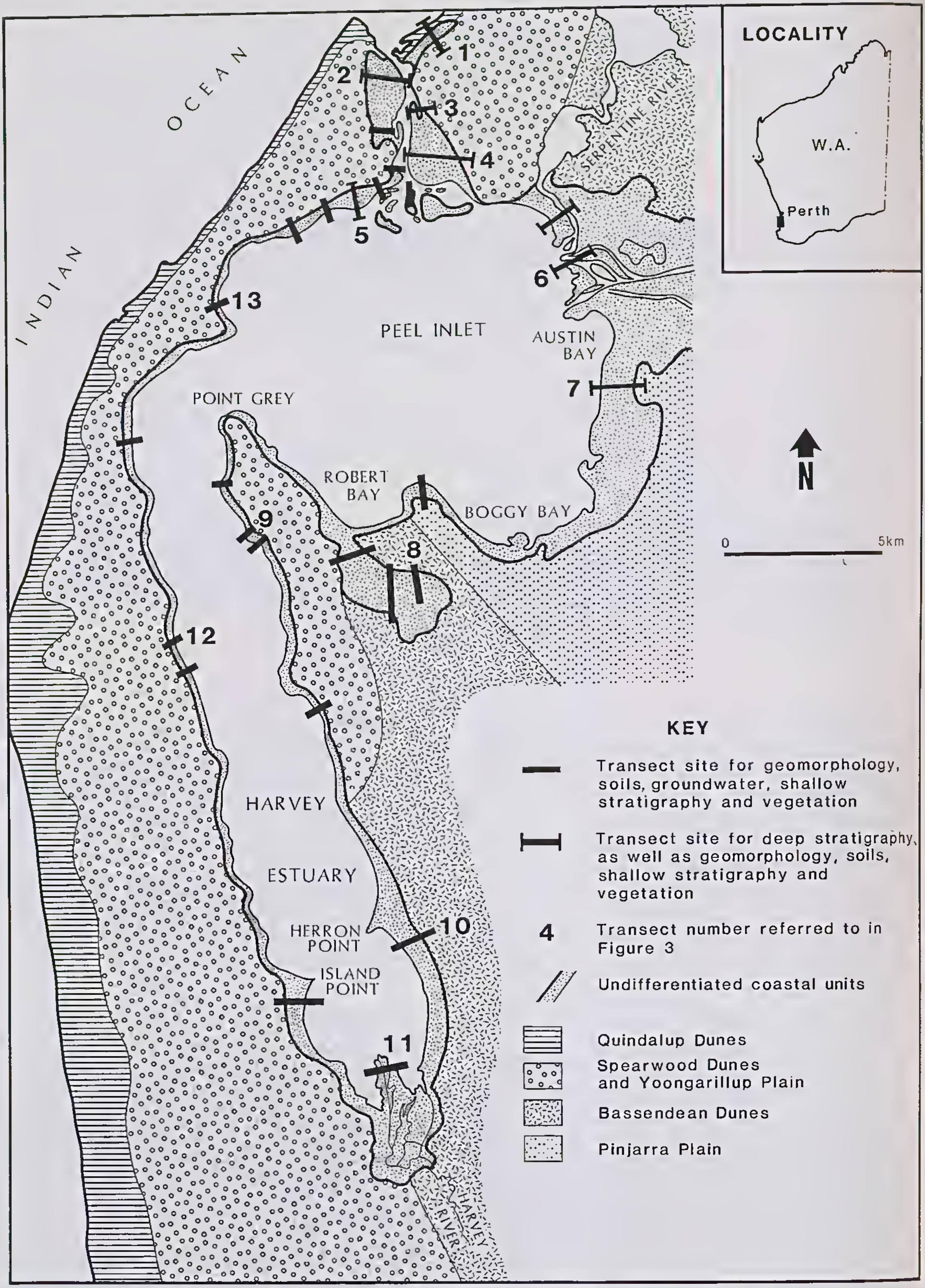
LOCALITY
W.A.
Perth
INDIAN OCEAN
PEEL INLET
AUSTIN BAY
POINT GREY
ROBERT BAY
BOGGY BAY
SERPENTINE RIVER
HARVEY ESTUARY
HERRON POINT
ISLAND POINT
HARVEY RIVER
N
0
5km
1
2
3
4
5
6
7
8
9
10
11
12
13
KEY
Transect site for geomorphology, soils, groundwater, shallow stratigraphy and vegetation
Transect site for deep stratigraphy, as well as geomorphology, soils, shallow stratigraphy and vegetation
4
Transect number referred to in Figure 3
Undifferentiated coastal units
Quindalup Dunes
Spearwood Dunes and Yoongarillup Plain
Bassendean Dunes
Pinjarra Plain

Figure 1 Locality map showing the Peel-Harvey estuary system within the framework of the major geomorphic units in the region (simplified after McArthur & Bettenay 1960), and location of the sampling transects of this study.

shoal complex. Overall, it is a difficult estuary to classify because it is complex. For instance, it is not easily classified using the scheme of Pritchard (1967) because its external form is due to marine inundation of three juxtaposed Pleistocene landforms that have been incised by three rivers.

The Peel-Harvey estuarine system has been described at the regional scale by Brown *et al* (1980) and Hodgkin *et al* (1980). The entire system is the estuarine confluence of three separate rivers, and is composed of 1) the circular Peel Inlet (the receiving basin for the Murray and Serpentine rivers), 2) the elongate Harvey estuary (the receiving basin for the Harvey River), and 3) the narrow linear exchange channel (which connects the estuary with the ocean). The main regional geomorphic components framing the system are (Fig. 1): a barrier ridge of Spearwood Dunes to the west; aeolian and fluvial lowlands of Bassendean Dunes and Pinjarra Plain to the east; and riverine discharge points (McArthur & Bettenay 1960). These units have an influence on the development of coastal landforms and sediments along the estuary shore. The wetlands within the Peel-Harvey system have been considered as a consanguineous group, and have been termed the Peel-Harvey Suite by Semeniuk (1988).

Climate

The climate of the area is subtropical, with hot dry summers and wet mild winters (Gentilli 1972).The important features for this study are rainfall, evaporation and wind. Rainfall is moderate, *c* 825 mm/yr, falling mainly in May to October (Bureau of Meteorology 1975); it recharges onshore groundwater reservoirs, provides runoff and groundwater discharge, waterlogs the estuarine peripheral flats, and seasonally dilutes the saline estuarine waters. Evaporation is high, *c* 1980 mm/yr; it has a major effect on the open waters and peripheral wetlands, because of the large surface area and relative shallowness of the estuary, and causes local hypersalinity in summer.

Wind generates wind waves, currents, littoral sediment drifts, and aeolian drifts. There are three wind systems that affect the region: cyclone-anticyclone winds, the landbreeze-seabreeze system, and storms (Gentilli 1972, Steedman & Craig 1983). During summer, with the anticyclone belt located to the south of the continent, winds in the region derive from E sectors, and landbreezes and seabreezes result in moderate winds from E sectors in the morning, and strong SW winds in the afternoon. In winter, with the belt to the north, winds derive from S to NW sectors. In winter there also are periodic storms deriving from SW to NW, but mainly from NW.

Hydrology

The estuarine system is a receiving basin for meteoric, fluvial, marine and ground waters, and peripheral wetlands of the area are maintained by one or more of these hydrological sources. Rainfall accounts for 20% to 30% of the fresh water input, while rivers and groundwater discharge account for the rest (Black & Rosher 1980). The rate of input and exchange of marine water is variable, depending on atmospheric conditions, rate of freshwater flow, and salinity of estuarine water. The estuarine waters fluctuate seasonally from brackish (mixed riverine and residual saline water from a previous season), to oceanic (when tidal exchange and wind mixing combine to flush the system of fresh water), to locally hypersaline (when summer evaporation and limited exchange cause elevation of salinity particularly at the head of Harvey Estuary). The uplands bordering the estuary are underlain by fresh groundwater. The contact of estuarine water and fresh groundwater is an inclined interface. Groundwater systems of the uplands function separately to the estuarine water body, although the water table in proximity to the estuary shows evidence of movements aligned to tidal fluctuations.

Hydrodynamics

The Peel-Harvey estuary is dominated by 5 main hydrodynamic processes: wind wave action; wind-induced current action; oceanic wave action; tidal exchange; and fluvial discharge. Wind waves and currents form within the estuary under the prevailing wind and storm conditions. The waves emanate from variable directions and are of variable wave length dependent on fetch. Because of the large fetch across Peel Inlet, winds from all directions are important in developing wind waves significant for shore processes. In contrast, the Harvey Estuary is influenced mainly by wind from SW and NW sectors. Oceanic wave action is located only within the exchange channel area and has components of wind waves and diffracted swell which have propagated through the exchange channel. The estuary is microtidal (Hodgkin & Di Lollo 1958, Easton 1970), and tidal exchange results in flood and ebb currents and water mixing, particularly within the exchange channel; these tidal currents, together with those induced by wind, are significant in transporting and accumulating sediment. Fluvial discharge results in influx of freshwater, generation of currents, transport of sediments, and mixing and flow into the ocean. The fluvial discharge is significant since it amounts to five times the volume of the estuary in a little over 4 months (Black & Rosher 1980).

Sedimentological Processes

The geomorphology of the shoreline and peripheral wetlands of the Peel-Harvey system are mainly the product of macroscopic sedimentologic processes, and these are briefly described as background to understanding the types and evolution of the shore. Smaller scale processes, such as bioturbation and current rippling, are not considered here as they merely modify sediments emplaced or shaped by the macroscopic processes. The sediments within the Peel-Harvey estuary have been derived from 5 sources (Brown *et al* 1980), *viz* fluvial, marine, internally reworked sediments, aeolian, and autochthonous biogenic sources. These result in sediments being composed of siliciclastic grains, clay minerals, skeletal components and organic detritus.

Numerous, varied, physical sedimentologic processes determine the location, configuration, extent, type and evolution of shore types and peripheral wetlands of the Peel-Harvey system, but they can be described under 3 main groups: estuarine; fluvial; and marine. Each dominates a geographic area and involves some mechanisms specific to that area.

Estuarine The estuarine sedimentological processes: wind-wave action, longshore drift, sediment transport and accumulation, and shoreward aeolian transport.

Wind waves erode, rework, resuspend and transport sediment in all environments. The major sites of accumulation by wind waves are the shorelines, where beachridges are formed, but additional constructional and destructional features resulting from wave action include shoal and spit accumulations, small cliffs and channels. Sediment eroded from shores may be transported offshore to accumulate on shelves and in basins. Mud, for instance, is transported in suspension throughout the estuary where, locally under relatively more quiescent conditions, such as basins, or lagoons behind emergent spits, it accumulates. The sedimentary shelves and the shallowness of the estuarine basins both act to dissipate wave energy, so that wave-developed landforms ultimately are best developed in areas facing long fetches. Longshore drift induced by wind waves and currents transports sediment reworked by waves. These currents build and shape the shoals at numerous sites along the shores of the estuary. Waves may be refracted around points and cuspate shorelines, resulting in extensive sediment accumulations, such as Point Grey and Island Point. Waves also contribute to the destruction of fluvial features of deltas. Wind transports any shoreline sediment further onshore to supplement the beachridge accumulations.

Fluvial Fluvial processes result in delta building in the estuarine basins. Lateral deltaic plains have formed by channel switching and crevasse splays. The prograding deltaic sediments coalesce with tidal deposits, while their shorelines are reworked into beaches, shoals and spits. The form of each of the 3 deltas (Fisher *et al* 1969) in this region reflects their hydrodynamic setting. The Harvey River delta is a high-constructive, elongate, fluvial-dominated delta. The Murray and Serpentine river deltas are coalesced, and because they front a large fetch across Peel Inlet, a high-constructive, lobate, more wave-dominated delta is formed.

Marine Marine processes extend into the estuary to influence sedimentation at the channel mouth and within the channel. The main factors induced by marine processes are: oceanic swell, wind and storm waves, longshore drift, and tidal currents. Oceanic swell and wind waves impinge on the channel mouth and translate along the channel length. These build sand bars, swash bars and shoals across the mouth on the ocean side, secondly, in conjuction with currents, transport sediment various distances along the channel, and thirdly, develop distinct sediment geometry along the exchange channel. Storm waves erode, transport and disperse sediment from the channel exit and also may erode, transport and disperse sediments from the marginal shoals within the channel. Longshore drift induced by waves at the oceanic mouth of the channel mostly transports sediment northwards along the coast such that there is no development of an ebb tidal delta. Ebb and flood tide currents within the channel transport marine sediment towards the estuarine basin where it accumulates in tidal-delta shoals and islands. These currents also shape the sedimentary bodies along the shorelines within the channel to form elongate, current-oriented shoals.

Criteria for recognizing shore types

The various shore types along the Peel-Harvey system are recognized and separated on criteria of: the shore terrain being in close (vertical) proximity to the prevailing estuarine water level and estuarine storm water level; geometry of shore; slope of shore; stratigraphy (geometry and lithologic suite); and similarity of formative processes (such as spit accretion processes versus beachridge accretion processes versus tidal delta accretion, *etc*). Since all the terrain is low lying, small scale features with relief less than 1 m become significant in comparing shore types, or deducing processes, or inferring history. It also is necessary in this type of study, where related shore types are grouped, to ensure firstly that they can be related to present or past Holocene estuarine processes, and secondly that a suite of shore types are linked in terms of common processes and origin. Consequently, some landform groupings in this paper differ from previous studies. Landform groups and boundaries along the north shore of Peel Inlet in this paper, for instance, differ from Brown *et al* (1980) both in the position of the boundary of the margin of the tidal delta and the exclusion of a spit-and-lagoon system from the tidal delta complex, because each has formed in a separate type of environment by different types of processes. The spit and lagoon complexes have formed mainly by eastward littoral drift; the tidal delta shoals have formed by flood tide sediment transport. Similarly, the inland extent of stranded estuarine lowlands in this paper differs from Brown *et al* (1980). The area of "estuarine lowland" along the east of Peel inlet in figure 3 of Brown *et al* (1980), on the basis of morphology and stratigraphy is the southern part of the flood plain of the Murray River. The landforms developed by estuarine processes, in contrast, are clearly peripheral to the estuary, or to stranded former embayments of the estuary, and are comprised of *shore-parallel* ridges, underlain by a distinct suite of sediments. Thus the criteria used here to determine whether coastal landforms of the Peel-Harvey system are estuarine, and form an inter-related estuarine suite, are that they show a "grain" or orientation in harmony with the estuary coast and with present processes, or are in concordant orientation with former embayments.

The shore types and peripheral wetlands of the Peel-Harvey estuary

The shores of the Peel-Harvey estuary are variable, dependent on the following interactive factors: hinterland type; sediment supply; dominance of estuarine *vs* fluvial *vs* marine processes, sealevel history, and geomorphic degradation. The peripheral wetlands are defined to be those portions of the estuarine coastal landforms that are permanently or seasonally inundated or waterlogged. The wetlands are sometimes well defined, as in the tidal delta and fluvial deltas, and locally more difficult to define because they coalesce with low lying hinterland terrain, or grade into ridge systems no longer influenced by estuarine processes. In the terminology of Semeniuk (1987), the wetlands are mainly basin types, but there are also flats and channels.

Many shore types and their associated wetlands encompass modern Holocene landforms, stranded (fossil) Holocene landforms, and Pleistocene landforms and sediments. Each shore type, and associated wetland, is a result of specific mechanisms of physical processes, sedimentary processes resulting in specific sediment types and geometry, water maintenance and hence water type, and longevity of inundation and waterlogging.

There are 12 types of estuarine shore, and they are listed in order of overall decreasing marine influence: 1) tidal shoals; 2) active tidal delta; 3) stranded channel shoal complex; 4) relict tidal delta; 5) stranded estuarine embayment; 6) spit-lagoon complexes; 7) beachridge complexes; 8) marginal platforms; 9) erosional sandy shore; 10) limestone cliff—pocket beach shore; 11) lobate fluvial delta complex; and 12) elongate fluvial delta complex. Artificial shores are not classified in this paper.

Ten of these shore types wholly or partly contain wetlands. The two that do not contain wetlands are the erosional sandy shore and the limestone cliff—pocket beach shore. Three of the shore types, *viz* the marginal platforms, beachridge complexes and spit-lagoon complexes are inter-gradational, and form an inter-gradational spectrum (or sequence). Each of the shore types are described below with regard to morphology, sedimentology, groundwater, vegetation and origin, and summarized in Table 1. The distribution of the shore types is shown in Fig. 2. Profiles and stratigraphy of the shores are illustrated in Fig. 3. Radiocarbon ages of the Holocene units and sealevel history of the area are presented and discussed in Semeniuk & Semeniuk (1990).

1 *Tidal shoals* The tidal shoals, situated in the tidal channel, are wholly wetland complexes. They are elongate, linear bodies, *c* 300 m long and 80 m wide, attached to the shore at their southern end. The shoals have developed as secondary features on the relict tidal delta and on the cuspate projections of the sandy hinterland. The shoals are aligned with the channel by tidal currents, and they protect shallower recessed bays which gradually have accumulated muddy sediment. The shoals have flat tops exposed at low tide; their margins gently slope to depths >1 m. The shoals are underlain by fine and medium sand, and locally, muddy sand. The vegetation colonising the tidal shoals consists predominantly of saltmarsh species of *Halosarcia halocnemoides*, *H. bidens*, *Suaeda australis*, *Frankenia pauciflora*, and *Muellerolimon salicorniaceum*. *Casuarina obesa* has established on the higher ground, forming bands and patches of low woodland.

2 *Active tidal delta* The active tidal delta also is wholly a wetland complex. It located at the southern end of the exchange channel and is a fan-shaped mosaic of emergent to subaqueous, dynamic shoals. These shoals are rounded to ovoid, ranging in size from 45 m to 600 m in diameter, and separated by distributary channels which scour through the subaqueous sand.

The edges of emergent shoals are eroded; there is a small cliff (15 cm high) with an accompanying perched sand ribbon. When accretion follows, the small cliff is often still evident as a stranded feature. The active tidal delta is underlain mainly by sand and shelly sand, and the emergent shoals are capped by a veneer of mud; the cliff edge of the emergent shoals is overlain by a thin ribbon of sand. The vegetation on the tidal delta is saltmarsh, similar to the tidal shoals. Saltmarsh gives way upslope to shrublands of *Melaleuca cuticularis* or woodland of *C.obesa*.

3 *Stranded channel shoal complex*. A stranded, or emergent, channel shoal complex, *c* 2.5 km x 1.0 km in size, occurs along the NW margin of the modern exchange channel. The surface of the landform is undulating, comprised of a series of very low relief (0.5-1.0 m) but wide, sand ridges and ellipsoidal sand hummocks (former sand waves and shoals), elongated sub-parallel to the former exchange channel margin, separated by low sinuosity shallow linear depressions and channels. At shallow depths the stratigraphy of the stranded channel shoal complex is relatively consistent: the landform is underlain mainly by shelly sand similar to modern estuarine sand shoal and sand flat facies, and represents a littoral to shallow sublittoral surface formed at a higher sealevel earlier in the Holocene; depressions in the landform, lying approximately at high water level, are filled by sand and mud sheets. Some of these depressions are seasonally inundated wetlands, while others are only seasonally waterlogged. At depths greater than 8 m, the stratigraphy consists of channel-fill deposits, with cut-and-fill structures.

The sand ridges and depressions of the stranded channel shoal complex, in their natural state, support *Eucalyptus gomphocephala* woodland, and assemblages of saltmarsh and shrublands and forests of *M. cuticularis*, respectively. However, much of the terrain has been cleared or developed into canal estates.

4 *Relict tidal delta* A relict tidal delta, *c* 1.5 km x 1.0 km in size, occurs along the SE sector of the modern exchange channel. The relict tidal delta largely is an emergent strandplain complex, formed at a higher sealevel earlier in the Holocene. The complex is composed of a flat terrain with relict (abandoned, infilled) tidal channels, and emergent shoals, onlapped by accreted sand and mud sheets which fill depressions lying approximately at high water level. Some of these depressions are seasonally inundated wetlands, while others are only seasonally waterlogged. The relict shoals may exhibit geomorphic patterns such as stranded sand ribbons and former erosional scars, illustrating their accretional history from smaller nucleus shoals. These patterns of accretion and erosion overall are sub-parallel to the margin of the active tidal delta. The stratigraphy of the relict tidal delta is variable over short distances, with lensoid veneers of sand and mud disconformably overlying shelly muddy sand, coarse quartz sand, or medium quartz sand, which in turn disconformably overlie limestone (that has an irregular surface and hence occurs at variable depth). The complex stratigraphy reflects the origin of the terrain that formed by accreting shoals, shifting channels, and filling of channels.

The variable substrates and depth related habitats of the relict tidal delta, in their natural state, support saltmarsh, shrublands of *M. cuticularis*, woodland of *Melaleuca rhaphiophylla* and *C. obesa*. However, much of this relict landform also has been cleared, infilled or developed into canal estates.

5 *Stranded estuarine embayment* Stranded estuarine embayments occur to the NE of the exchange channel and to the south of Peel Inlet. The first stranded embayment adjoins the exchange channel, and comprises an elongate estuarine lowland formed behind a barrier dune. At present the lowland is a series of wetlands underlain by tidal estuarine deposits, but was formerly connected to the exchange channel (see Fig. 12 B,C of Searle *et al* 1988). Apart from some isolated stands of *M. rhaphiophylla* and *Acacia* spp, no natural vegetation remains on this landform.

Table 1

Description of shore landforms of the Peel-Harvey estuary

Unit	Main features	Stratigraphy	Main formative Processes	Main sediment-ologic Processes	Wetland Type	Groundwater[1] Characteristics	Vegetation
1 Tidal shoals	Microscale inter-tidal & subaqueous shoals aligned with exchange channel	Root structured & bioturbated mud, muddy sand & shelly sand	Tidal currents wind waves	Sediment transport by ebb & flow currents; trapping by vegetation	Estuarine tidal flat	Poikilohaline: Mesosaline	C. *obesa* woodland; saltmarsh of *H. halocnemoides, H. bidens, F. pauciflora, S. australis, S. quinqueflora*
2 Active tidal delta	Microscale tidal & subaqueous shoals & channels	Sand & shelly sand capped by a veneer of mud.	Energy loss of tidal currents due to enlarged receiving basin	Deposition by tidal currents; intermittent erosion by storms or heavy river discharge	Estuarine tidal flat	Poikilohaline: Mesosaline to hypersaline	C. *obesa* woodland; saltmarsh of *H. halocnemoides, H. bidens, S. quinqueflora*
3 Stranded channel shoals	Undulating terrain of sand ridges & hummocks, with intervening shallow depressions	Sand & shelly sand with mud veneers	Shoals & channels formed at a higher sealevel	Relict, stranded system	Linear basins, flats, shallow channels	Poikilohaline: Mesosaline to hypersaline	Ridges: *E. gomphoceplala* woodland; Depressions: *M. cuticularis* scrub & closed low forest; saltmarsh with *H. bidens*; otherwise mostly cleared
4 Relict tidal delta	Strandplain complex of flats, very low shoals & depressions	Veneers of sand & mud overlying channel-fills of sand/shelly sand, & shoal sand, over-lying limestone	Shoals & channels formed at a higher sealevel	Relict, stranded system	Flats & shallow basins	Varies from hyposaline to mesosaline	C. *obesa* woodland; saltmarsh of *H. halocnemoides, H. bidens*
5 Stranded estuarine embayment	Mesoscale basins, locally ringed by low beachridges	Estuarine mud or shelly mud, over-lying sand	Filling by estuarine sedim-entation during higher sealevel	Relict, stranded system	Basins	Poikilohaline: fresh/subhaline to hypersaline	Zoned assemblages of *M. uncinata, Acacia* spp., *M. hamulosa, H.* spp.
6 Spit-lagoon complex	Mesoscale complex of emergent spits & inter-ridge lagoons	Mud overlying quartz sand in the lagoons. Muddy sand overlying quartz sand in depressions.	Waves, longshore currents	Shoreward transport by waves; longshore movement by currents in northerly direction	Linear basins	Poikilohaline: varies from fresh to hyper-saline.	Spits: *E. gomphocephala* woodland, *J. furcellata* scrub, *Acacia* scrub; Spit margins: *M. rhaphiophylla* forest & *E. rudis* woodland; Depressions: *R. inops* scrub, *M. leptoclada* scrub, *M. hamulosa* scrub/heath, *M. cuticularis* low forest, *M. rhaphiophylla* scrub, *M. uncinata* scrub, *J. kraussii* sedgeland, *Sarcocornia-Halosarcia* saltmarsh

Table 1—*continued*

Description of shore landforms of the Peel-Harvey estuary

Unit	Main features	Stratigraphy	Main formative Processes	Main sediment-ologic Processes	Wetland Type	Groundwater[1] Characteristics	Vegetation
7 Beach-ridge complex	Shore parallel microscale ridges	Quartz sand overlying buried muddy sand or sand	Waves, wind.	Waves accrete sediment into shoreline ridges which are later capped by aeolian sediments	Linear basins	Fresh inland, mesosaline near the estuary.	Ridges: *R. inops* closed scrub, Depressions: *C. obesa* woodland, *M. rhaphiophylla* scrub, *M. cuticularis* scrub, *M. leptoclada* heath, *J. kraussii* sedgeland, *Halosarcia* saltmarsh
8 Marginal platform	Shore parallel microscale bench	Mud & muddy sand overlying sand	Waves, tidal sedimentation	Waves build up sediment against limestone cliffs	Flats & very shallow basins	Poikilohaline: subhaline to hyposaline	*M. rhaphiophylla* low forest, *M. cuticularis* low forest, *J. maritimus* sedgeland
9 Erosional sandy shore	Microscale cliff & narrow shore	Fine, medium & coarse quartz sand	Erosion & alongshore transport by waves & currents	Longshore currents, & wave erosion	none	Subhaline to hyposaline	*E. calophylla* woodland, with u/s *J. furcellata* & *K. ericifolia*; narrow fringe of *J. kraussii* sedgeland, *S. australis* herbland & shrubland of *M. rhaphiophylla*, *M. cuticularis*, *M. hamulosa*
10 Limestone cliff pocket beach	Limestone cliffs & pavement with local overlying sand on estuarine floor; intervening narrow microscale steep pocket beaches	Sand veneer overlying limestone	Erosion by shoreline currents & wind waves	Erosion of sand & limestone by currents, waves, & solution	None	Same as estuary: poikilohaline	*C. obesa* woodland; sandy shore colonized by *J. kraussii* sedgeland, *S. australis* herbland, *M. cuticularis* shrubland
11 Lobate fluvial delta complex	Macroscale lobate delta: distributary channels, levees, lakes, flats, basins, mid-channel islands, ridges	Mud overlying quartz sand in depressions, quartz sand on ridges	Deltaic processes; estuarine processes; reworking by waves & currents	Deltaic sedimentation; wave reworking of sediment	Channels, basins flats	Poikilohaline: subhaline to hypersaline	*C. obesa* forest, saltmarsh of *H. halocnemoides*, *H. bidens*, *S. quinqueflora*
12 Elongate fluvial delta	Macroscale elongate delta: distributary channels, levees, flats; broad deltaic plain	Mud overlying sand, or mud overlying sand overlying muddy sand	Deltaic processes; estuarine processes; reworking by waves & currents	Deltaic sedimentation; wave reworking of sediment	channels, basins flats	Poikilohaline: hyposaline to hhypersaline, & brine	*M. rhaphiophylla* low forest, *M. cuticularis* low forest, *C. obesa* low forest, *M. uncinata* shrubland, *M. hamulosa* shrubland, *Halosarcia-Suaeda* herbland, *J. kraussii* sedgeland

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[1] Water characteristics vary spatially and temporally. Salinity terms (after Hammer, 1986) are as follows: fresh—0-1 000 ppm TDS, subhaline—1 000-3 000 ppm TDS, hyposaline—3 000-20 000 ppm TDS, mesohaline—20 000-50 000 ppm TDS, hypersaline—50 000-80 000 ppm TDS, brine—>80 000 ppm TDS.

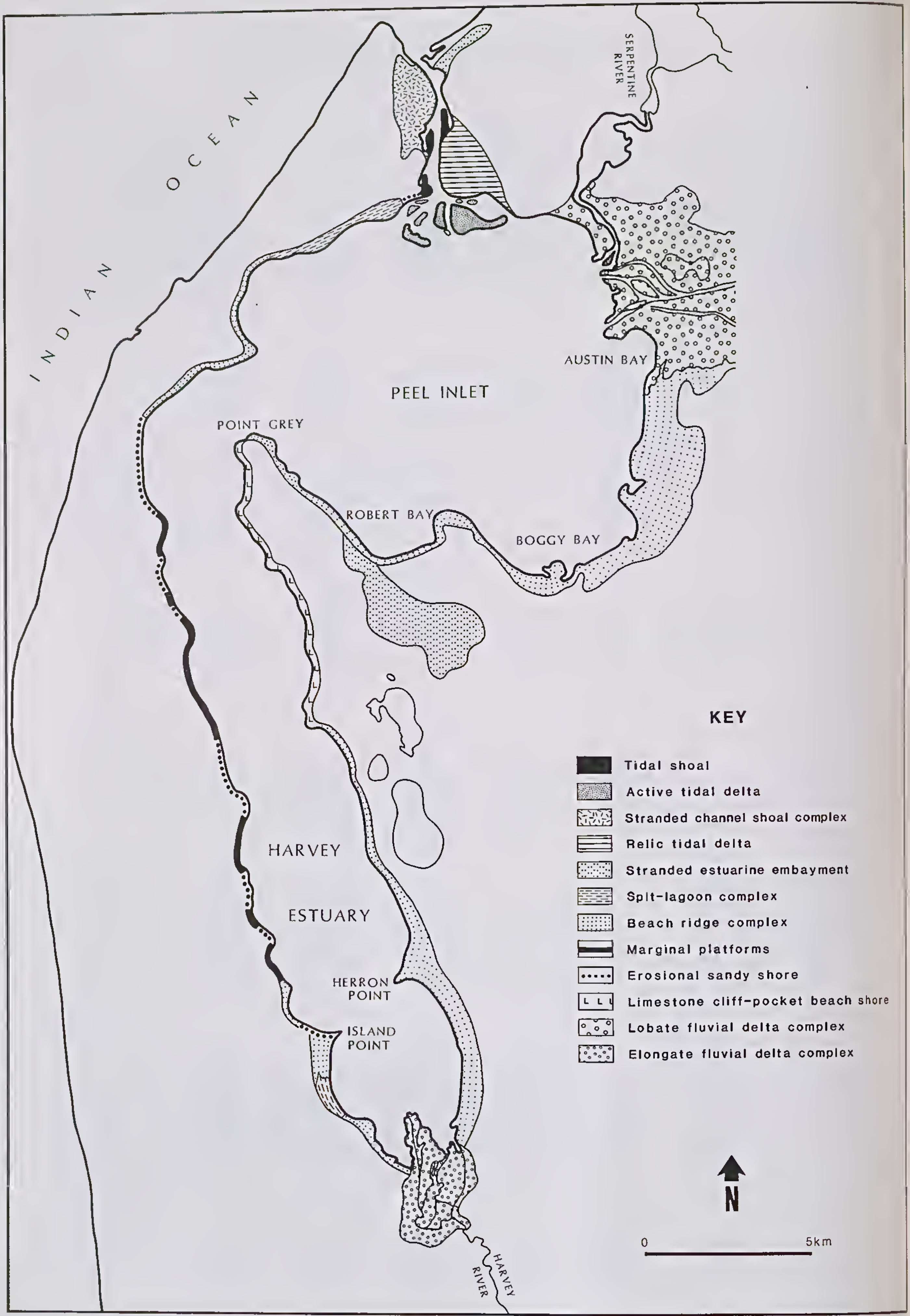

Figure 2 Distribution of the shore types along the Peel-Harvey estuary system.

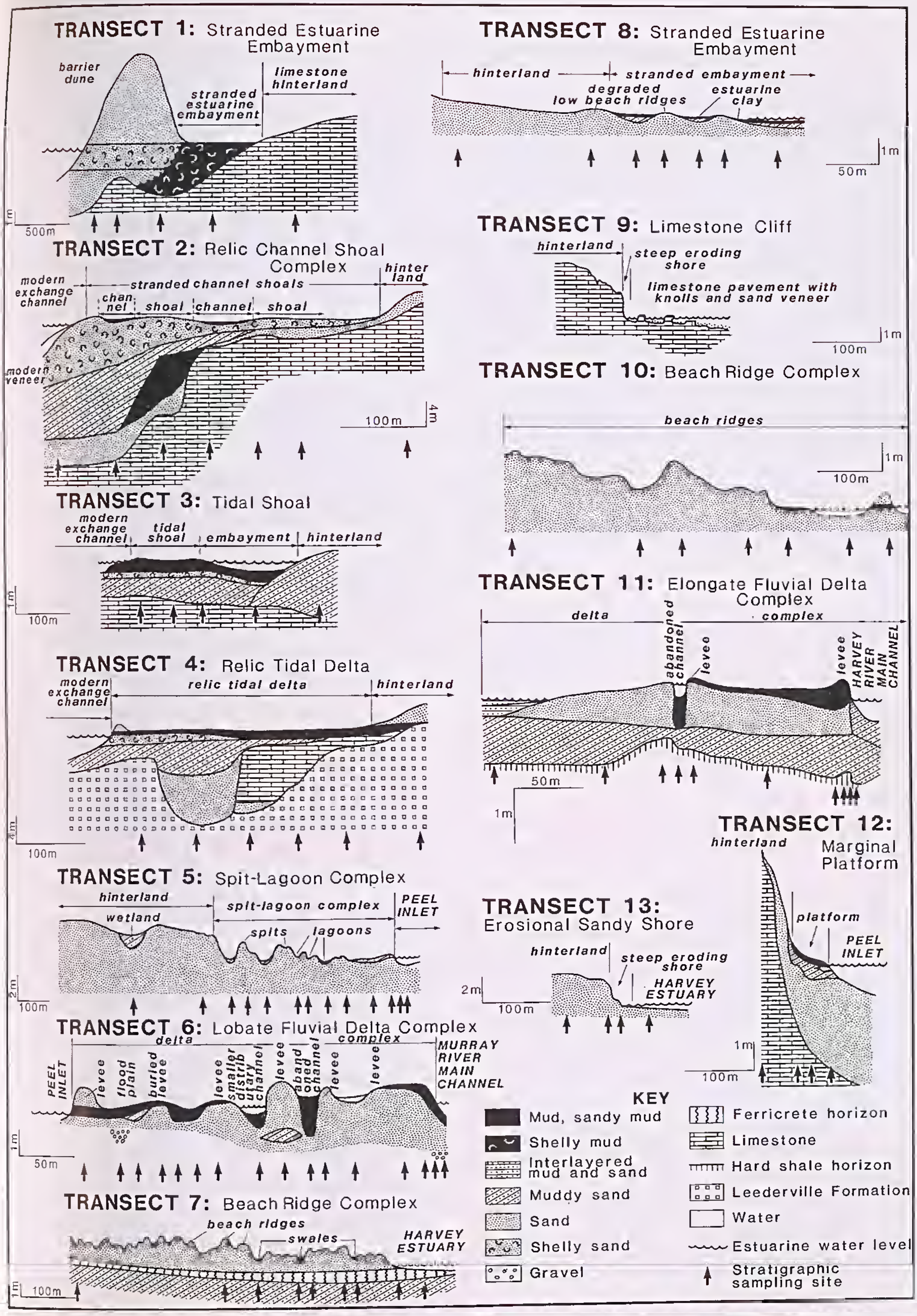

Figure 3 Stratigraphic profiles across each of the main shore types in the Peel-Harvey estuarine system. Location of the transects is shown on Figure 1.

The second stranded embayment is large elongate lowland (wetland) that was formerly a shallow estuarine embayment connected to Peel Inlet by a narrow-necked entrance. The former embayment was developed by estuarine flooding of a wetland basin that was the northern extension of a chain of sumplands comprising the Bibra consanguineous suite in this area (Semeniuk 1988). The margins of the lowland are ringed by a concentric series of low, degraded beachridges. The stratigraphy of the system consists of thin veener of estuarine clay overlying quartz sand both in the main embayment and in the linear depressions between the beachridges; the beachridges are underlain by quartz sand. Vegetation on the terrain consists of zoned assemblages of *Melaleuca uncinata* on the higher ground, grading to *M. hamulosa* and *H. bidens* in the wetter areas.

6 *Spit-lagoon complex* The spit-lagoon complex is composed of a series of overlapping to adjacent, emergent, shore-parallel to recurved, narrow spits, built by waves and longshore currents, that enclose elongate to elliptical lagoonal (wetland) depressions. The spit-lagoon complexes occur along the NW shore of Peel Inlet and the SW shore of Harvey Estuary. The complexes are best developed and at different stages of development in the NW of Peel Inlet, where up to 5 main spits can be differentiated. Each spit and lagoon complex is *c* 1 km long by 300 m wide. The spits are *c* 70-100 cm high, *c* 30 m wide, and spaced between 20-100 m apart. The youngest spit occurs at the outer edge of the complex, and the interior of the system is a series of progressively older spit ridges dividing the area into elongate basins or depressions. The spits emanate from the same locus to the west, and extend in a NE to E direction; they overlap part of their length, but terminate at different places. Some spits bifurcate or recurve inwards for short distances along their length. The sediments underlying the spit-lagoon complexess are fine/medium quartz sand with lenses of mud veneering the surface of depressions. The wetland depressions between the spits vary from permanently to seasonally inundated, and both estuarine and groundwater sources maintain them. Ponding of meteoric water or estuarine flood water becomes significant where there are buried mud lenses.

Spit-lagoon areas are colonized by a complex variety of vegetation assemblages which are related to substrate, water table level, topographic height and salinity. The assemblages found associated with the spits are 1) sedge of *Isolepis nodosa* and *Juncus kraussii*; 2) closed scrub of *Jacksonia furcellata—Acacia* sp—*Regelia inops;* and 3) woodland of *Eucalyptus rudis* with understorey of *J. furcellata.* The margins of depressions are colonized by one to several peripheral bands of vegetation such as 1) scrub of *M. rhaphiophylla* and *M. uncinata;* 2) scrub of *M. rhaphiophylla*; or 3) closed heath of *Regelia inops* and *M. leptoclada.* The centres of the depressions are vegetated by 1) saltmarsh (*Sarcocornia* sp., *Suaeda australis, Halosarcia halocnemoides* and *H. bidens;* 2) scrub of *M. cuticularis;* or 3) low closed forest of *M. rhaphiophylla* with an understorey of *M. hamulosa* and *M. leptoclada.*

7 *Beach ridge complexes* Beach ridge complexes occur on the E shore of Peel Inlet south of the Murray delta (Austin Bay area), on the W shore of Peel Inlet, on the E and W shore of Harvey Estuary (Herron Point area and south of Island Point, respectively), and as a stranded ribbon feature, onlapped by deltaic deposits, to the SE of the Harvey River delta. Beach ridges are ribbon-shaped and extensive along the shore. They are usually 300-400 m wide, but in some areas up to 600 m wide. They are comprised of sand ridges *c* 50-70 cm (to 1 m) high, and spaced 10-20 m apart with intervening (wetland) swales. The continuous nature of parallel ridges often is disrupted by one of three patterns: 1) discontinuous but still aligned ridges; 2) segments of parallel ridges separated by lagoons, shallow basins, or flats; and 3) short segments of parallel ridges in different orientations coalescing or merging with the main set. These patterns result form earlier cycles of reworking and redistribution of beach ridges by waves, and modification of beachridge orientation by sediment discharge from runoff channels. The landward margin of beach ridges grades into uplands, while the estuary margin usually is reworked into disconnected spits and shoals within the estuary. Locally, the estuary margin is irregular, and may include coastal indentations, small cuspate forelands, scalloped shores and projections.

The stratigraphy of the ridges in the Austin Bay area consists of 1-2 m of aeolian, medium sized quartz sand overlying muddy sand or sandy mud, which overlies sand at depths of 13 m. The stratigraphy of the ridges in the Herron Point area consists of 1-2 m of aeolian, medium sized quartz sand overlying medium and coarse quartz sand to depths of 6 m. Along the west shore of Harvey Estuary south of Island Point, the shallow stratigraphy is more complex, with surface and buried lenses of mud interspersed with sand spit/ridge deposits. All ridges in the various areas have been further eroded by wind and sheet wash so that swales are infilled by sand to varying degrees, and capped by humic or peaty soil. Adjacent to the estuary there are occasional veneers of mud in locally broad inter-ridge depressions and lagoons.

The wetlands in the beachridge complexes are inter-ridge depressions which rise to progressively higher levels above the estuary further from the shore. The water table lies *c* 50-100 cm below the surface of the wetlands, but rises to within 20cm of the surface under the near-estuary depressions. The wetlands are maintained by minor tidal inundation, or seasonal groundwater inundation, or seasonal waterlogging. The sand ridges are colonized by 1) closed heath or closed scrub of *Acacia* spp, *R.inops, J. furcellata;* 2) closed heath of *Homalospermum;* 3) scrub of *Kunzea ericifolia;* 4) low open woodland of *Melaleuca preissiana* and/or *C. obesa* with an understorey composed of elements from 1), 2) and 3) above. The swales are colonized by 1) saltmarsh (*Halosarcia* spp and *Suaeda australis;* 2) sedgeland of *J. kraussii;* 3) closed heath of *Actinostrobus pyramidalis;* 4) closed heath of *Melaleuca incana;* 5) low closed heath of *M. leptoclada;* 6) low closed heath of *Homalospermum* and *R. inops;* 7) patchy scrubland of *M. cuticularis;* and 8) low closed forest of mixed *C. obesa, M. rhaphiophylla, M. cuticularis* and *M. hamulosa.*

8 *Marginal platforms* Marginal platforms are narrow wetlands located on the western shore of Harvey Estuary between the limestone ridge of the barrier and the subaqueous shelf of the estuary. They are narrow linear platforms, or benches, *c* 25-90 cm above the water level of the estuary, with widths ranging from 25 m around headlands to 100 m within small bays. The contact of platforms with the estuary either is gradual, or marked by

a break in slope. The gradient of the platforms is related to their width. Wide platforms have nearly planar surface, while narrow platforms exhibit slopes up to 1:20. Sediments underlying the platforms consist of a thin veneer of mud grading via muddy sand into medium to fine quartz sand and finally limestone at depths of *c* 3.5 m. The wetland hydrology is maintained variably by estuarine water in some areas, or groundwater rise, or ponding by the mud veneers. The marginal platform wetland is inundated seasonally by estuarine water, and the water table falls to -50cm in the drier months. Marginal platforms are colonized by mixed low woodland comprising *M. rhaphiophylla*, *M. cuticularis*, *M. hamulosa* and *E. rudis* with an understorey of marsh plants and sedges of *Sarcocornia* spp, *Suaeda australis*, *J. kraussii*, and *Gahnia trifida*.

9 *Erosional sandy shore* This shore type mainly occurs on the western side of Harvey estuary interspersed with the marginal platform shore type; the erosional sandy shore predominates around the nodes or more exposed stretches of the coast while the marginal platform type is located in the small scale indentations. The shore type also locally occurs along the shore of Peel Inlet and the modern exchange channel. The slope of erosional sandy shores most commonly ranges between 1:10 to 1:5, but may form a small cliff (<1 m). Shore erosion is evident both in the slope and the exposure of underlying stratigraphy. The sediments along this shore type usually are quartz sand of mixed grain size, with occasionally a thin layer of muddy sand exposed just below the surface. Erosion generally has incised into the hinterland such that woodlands of *Eucalyptus calophylla* border the shoreline, with an intermittent thin fringe of *J. kraussii*.

10 *Limestone cliff—pocket beach shore* This shore type is comprised of an eroding limestone shore alternating with small pocket beaches. The shore type occurs along the eastern side of Harvey estuary from Pt Grey southwards for *c* 7 km. Limestone forms cliffs and discontinuous littoral to sublittoral pavements around headlands and points, and steep sloped pocket beaches, less than 8 m wide, form along the intervening straight stretches. The pocket beaches are backed by relict beach ridges or Pleistocene dunes. Quartz sand is the dominant sediment of the pocket beaches. The vegetation on some limestone headlands consists of low closed forests of *C. obesa*, along the front of which is a narrow and often discontinuous fringe of *M. cuticularis* shrubs and *J. kraussii* sedge. The sedge fringe also colonizes the shore edge of the intervening beaches. Other limestone headlands are vegetated merely by the hinterland assemblages.

11 *Lobate fluvial delta complex* A wetland complex comprised of a lobate fluvial delta is situated along the NE shore of Peel Inlet, and is the combined delta system of the Serpentine and Murray rivers. Although the delta is a high-constructive type, wave reworking of the shore has resulted in the development of shore-parallel, low beachridges, separated by inter-ridge swales and flats. The deltaic lobe is 5 km wide at its apex. The Murray River is the dominant system for transporting sediment and constructing the delta. The present main channel of the Murray River is straight and flows along the central axis of the complex. The main channel divides into 7 distributaries, with associated mid-channel islands; one of the distributaries coincides with the Serpentine River distributary channels. There is a large deltaic plain adjoining the channels, and this can be divided into the following features: 1) abandoned channels, 2) levees, 3) lakes (= former, abandoned inter-distributary basins), 4) flats, 5) basins, 6) ridges and 7) hummock/swale system (= degraded levee system).

Inter-distributary flats and basins comprise most of the deltaic plain. They are small to medium scale wetland depressions separated by low-relief ridges which recurve and bifurcate. The depressions range in shape from narrow-linear to ovoid. There are now 3 abandoned channels, with associated levees, which are completely enclosed by the deltaic plain. However, flood water from these channels enters either the active channels or the estuary itself via basins and flats or drains. Ridges which occur on the deltaic plain are levee deposits, former spits and aeolian deposits; they are small scale and localized.

The stratigraphy of the delta is variable and complex, depending on formative environment, history and age of particular units. There are interlayered sheets, lenses and shoe-strings of various grain sizes of sand, muddy sand, sandy mud, mud, and at depth, coarse river gravel, and gravelly sand. Consequently, the hydrology of the system and its wetlands also is complex, depending on the stratigraphy, source of water, water dynamics, and distance from estuary shore.

The description of vegetation on the lobate delta is confined to the proximal end of the delta. The leptoscale channels of the deltaic plain are colonized by saltmarsh (mainly *Halosarcia* spp). The levees are colonized by *Halosarcia* spp. The ridges are colonized by *C. obesa* woodland with an understorey of open shrubland of *M. hamulosa* and open sedgeland of *J. kraussii* and *I. nodosa*. The depressions are colonized by saltmarsh (*Sarcocornia quinqueflora*, *H. halocnemoides* and *H. bidens*. The margin of the delta with the estuary is colonized by a mosaic of all of the above species.

12 *Elongate fluvial delta complex* An elongate fluvial delta (or birds foot delta), and an associated stranded deltaic plain, has been developed by the Harvey River. The normal components of such deltas are all present, ie distributary channels, levees, inter-distributary bays, subaerial plain and pro-delta slope. Consequently there are a wide range of wetland habitats within the deltaic complex. The modern, or active, delta is 2.5 km long, with a single, almost straight channel which divides into 4 distributary channels at the delta front. There also are several abandoned channels, also lined with subaerial levees. The inter-distributary basins range from sublittoral, to littoral, to seasonally inundated basins and flats. The older depressions in the deltaic plain are influenced by groundwater, while those at the front of the delta are influenced by estuarine flooding. The stranded deltaic plain has components of abandoned channels, levees, basins, and flats. The stratigraphy of the entire modern and stranded system consists of complex array of shoestrings of sand and mud, interspersed with sheets of sand and mud, representing units formed in channels, in abandoned channels, levees and on floodplains.

The vegetation on this delta comprises assemblages of mixed low forests of *C. obesa*, *M. cuticularis* and *M. rhaphiophylla* on the levees; assemblages of scrub of *M.*

rhaphiophylla, *M. hamulosa*, and *M. uncinata* on the abandoned levees; and assemblages of saltmarsh, dominantly of *Halosarcia* spp, on the flats and depressions.

Discussion

The results of this paper are discussed below in terms of variability of shore types, internal complexity of shore types and wetlands, the physical basis of the shore types and wetlands for developing vegetation habitats, and the peripheral vegetation response, and the research, education and conservation significance of the area.

It is apparent that a wide range of shore types and wetlands comprise the Peel-Harvey estuarine system, a factor that perhaps has not been fully appreciated by previous workers. Because of its large size, the estuarine system transcends several regional geomorphic units, and it could be anticipated that a variety of shore types would be developed. Overall, the range of macroscopic shore types are intimately linked to geographic location within the estuary (reflecting hydrodynamic setting), and to the type of hinterland backing the shore. For instance, the dynamics of the exchange channel environment has resulted in the development of modern tidal shoals and a tidal delta, and their stranded, relict equivalents. The discharge sites for the regional rivers have resulted in the development of deltas. Where the estuary shore is incised into the Spearwood Dunes, there are eroding limestone shores, eroding sandy shores, steep shores with fringing platforms, and locally, beachridge complexes and spit-lagoon systems. Shores fringing the terrain of Bassendean Dunes are beachridge complexes. Elsewhere, along the remainder of the estuary system, dependent on wind, fetch, and sand supply, beach ridge complexes are developed to varying extent and widths. Compounding this inherent variablity due to regional factors is the effect of small scale processes that result in local variation in shore landforms and associated wetlands within any given area.

Within any given setting, the shore landforms and wetlands may be internally simple or complex. The marginal platforms and beachridges are simple systems, and spit-lagoon complexes and deltas are complex systems. The complexity of a shore landform and its associated wetlands is related to a variety of interacting features such as regional setting and aspect, local sedimentological processes, sealevel history, distance from and height above the estuary, and groundwater characteristics. This complexity also has not been fully appreciated by previous workers, and we consider it to be a critical feature to understanding the complexity of the types and distribution of the vegetation units that occur in this area.

Backshall & Bridgewater (1981) carried out a study of vegetation types, soil salinity and regional soil types, along the estuarine fringe, and produced a list of vegetation assemblages. Their study forms only the shoreward part of the shore-and-wetland study of this paper, and consequently their study accents the assemblages of the tidal marshes. This paper has tended to emphasize the full gradation of landforms and vegetation habitats from the estuarine shore through to the hinterland.

Vegetation variablity, both in terms of floristic complexity of assemblages and their distribution [as laterally extensive formations, peripheral strips and fringes, or as mosaics], is a direct response to habitat features, ie shore landform heterogeneity. Thus the description of the variable shore types and their associated wetlands provides a physical basis to understanding the development of habitats for vegetation. The internal heterogeneity of habitat types within a shore type or wetland result in a complex arrangement of vegetation formations *within* a given landform, or even subunit within a landform. However, it must also be emphasized that, given there is only a limited species pool of wetland vegetation in the region, within these vegetation formations the floristic composition can be relatively simple. The species recur through all wetland types but in variable structural formations, variable alliances, variable abundance and luxuriance. This variability can be determined by the physical factors of availability of water, consistency of water salinity, the lateral extent of uniform sedimentary substrates, height above the water table, shore slope, and protection from wind and waves.

The variability of shore types and wetland types along the extent of the estuarine shores, the internal heterogeneity of landforms and habitats within any given shore type, and the complex arrangement and distribution of vegetation in response to regional scale and local scale habitat differences highlight a need to preserve various tracts of shore for purposes of conservation, research and education. Clearly, the various delta types would need separate preservation. The transition from estuarine-influenced beachridges and wetlands through to hinterland freshwater-influenced beachridges illustrate a close relationship of landform, history and vegetation response that also need to be preserved at least for research and education purposes. Unique areas, such as the spit-lagoon complex in the NW Peel Inlet area and the elongate Harvey River delta, provide classic examples of vegetation and landform inter-relationships that are useful for research and education. Finally, areas of elevated (or stranded) deposits that were formed in the middle Holocene, *eg* the relict tidal delta, the stranded channel shoal complex, or the beachridges of the western Harvey Estuary Island Point area, provide valuable resources of information about sealevel history, Holocene climate history and long-term estuarine dynamics useful for research purposes.

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Youndegin meteorite shower: a re-assessment of provenance

W H Cleverly[1] & E I Cleverly[2]

[1]Western Australian School of Mines & [2]79 Ward Street, Kalgoorlie-Boulder WA 6430

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Abstract

Field and literature searches have resulted in some modification of the generally accepted find sites of the Youndegin meteorites. A metallic object found 1.9 km NW of Pikaring Hill (32°05'S, 117°43'E) near the find site of Youndegin I-IV might be the small Youndegin iron of 4.66 kg held by the Quairading District High School: Youndegin VII might also have been found in that vicinity. Youndegin V and VI were found within 5 km of Pikaring Hill, not near Wogerlin Hill. The find site of Quairading (Youndegin IX) at 32°09'S, 117°40'E has been re-visited. The precise find sites of the Mount Stirling and Mooranoppin irons remain unknown. No evidence was found that a so-called "crater" near Pikaring Hill was formed by meteorite impact. A tentative strewnfield delineated for the shower indicates atmospheric passage in a westerly direction.

Introduction

The first recoveries of the Youndegin meteorite shower were made near Pikaring Hill, Western Australia in 1884. The meteoritic nature of the material was recognized almost immediately (Fletcher 1887). The name adopted for the meteorite was that of the police outpost at Youndegin, 50km NW of the find site (Fig. 1). These finds and others in the succeeding 45 years were named variously Youndegin I-VIII, Mount Stirling, Mooranoppin I and II and Quairading. The common origin of these masses was demonstrated by de Laeter (1973). A comprehensive account of the meteorite has been given by Buchwald (1975). An additional member of the shower has since been described by de Laeter & Hosie (1985) and a further small mass is currently being examined by A W R Bevan. The investigation of this meteorite thus spans more than a century but only one of the finds is known to have been seen in the field by a scientist and no other field work of any kind was carried out. The present work seeks to rectify the omission but with inevitable limitations arising from the poor definition of some find sites and the lapse of more than 80 years since the major finds were made.

Individual finds

Youndegin I-IV The four irons and abundant iron shale derived from a fragmented and/or disintegrated mass of more than 33 kg were found about 1.2 km NW of the top of Penkarring Rock (Fletcher 1887), now known as Pikaring Hill (Fig. 1). The reported site is about central to Avon Location 14 756 (Fig. 2), now part of the farm of C A & B J Hughes. We searched the vicinity unsuccessfully.

Mr C A Hughes stated that a lump of metal, "double fist-sized, very heavy, not cut by a hacksaw" had been found about 20 years before (*c* 1968) by Mr N Bartlett at a point which he indicated near the NW corner of Location 14 756 (Fig. 2). The object was taken to the Shenton Machinery Co in Quairading where an attempt was made to cut it. Its subsequent history is unknown to Mr Hughes. The vicinity of this find was also searched unsuccessfully.

Youndegin V and VI Mr Louis Knoop found Youndegin V of weight 174 kg in 1891 and Youndegin VI of weight 924 kg in 1892; together with Youndegin I-IV, they were within a radius of *c* 5 km on the Peekerin (Pikaring) sandplain (Anon 1893a). Knoop sold both masses to the mineral dealer J R Gregory of London (Gregory 1892, Anon 1893b). The precise find sites were not disclosed (Glauert 1954).

We are unable to find any justification for the assumption made by Grace & Lemesurier (1954)—more than 60 years after the event—that Knoop found Youndegin V & VI on property which he was said to own 10 miles (16 km) N of Corrigin, *ie* near Wogerlin Hill. This hill, located 32°10'S, 117°50'E, but with longitude incorrectly stated as 118°50'E, has been widely quoted as the find site.

Youndegin VII This mass of 4.1 kg was found by a Mr Finkelstein in 1929 on Finkelstein's farm, which is shown on a small scale map as a single point *c* 6 km NE of Pikaring Hill (Simpson 1938, Fig. 1). Dr Simpson's Mineral Collection Catalogue 1897-1936 records the find site as Avon Location 19 493, which is centred 32°02'S, 117°45'E (Fig. 2). However, the point indicated by Simpson (1938) and widely accepted as the find site was—at least approximately—the farmhouse and Location 19 493 was

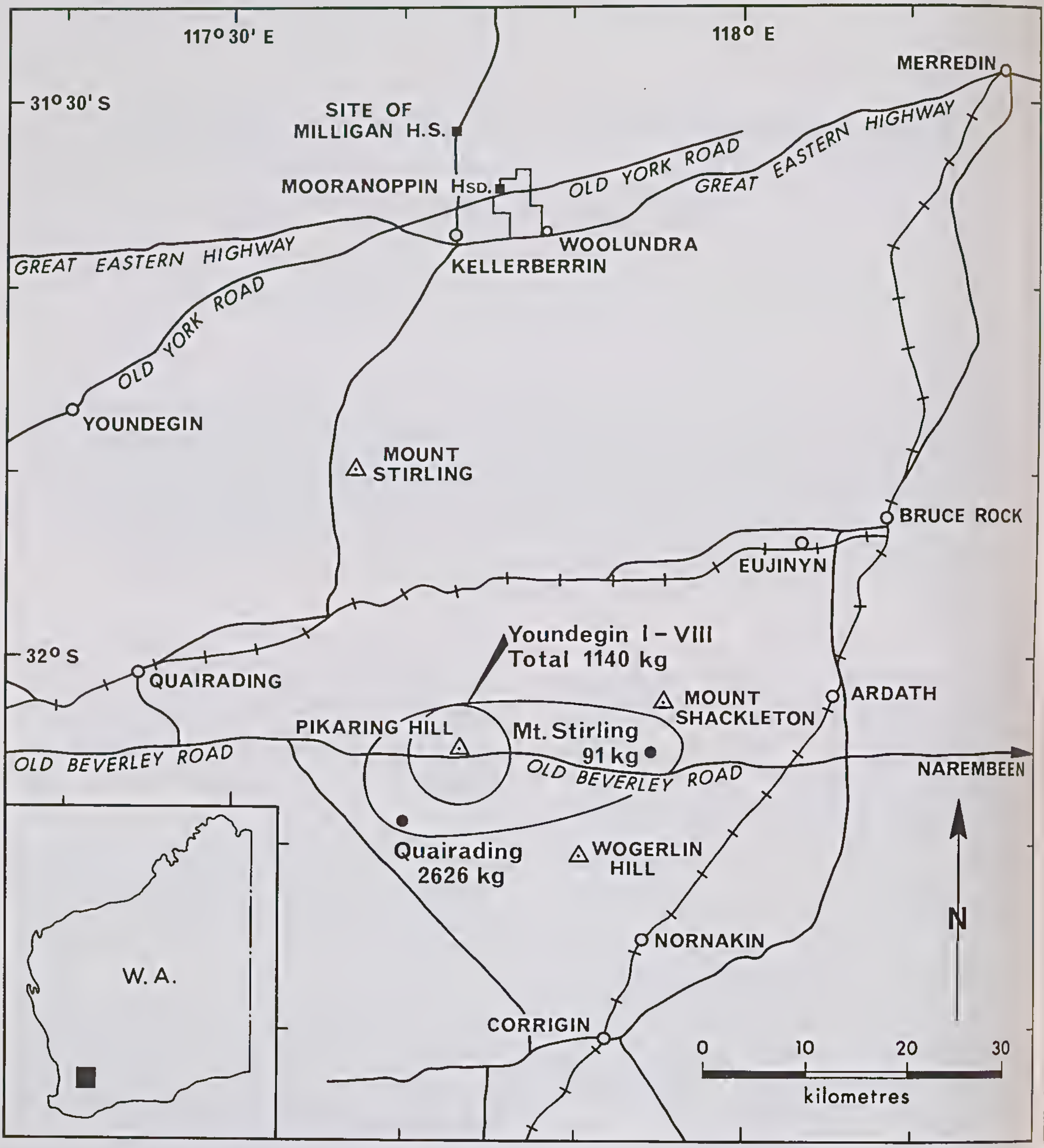

Figure 1 Map of part of Western Australia. Meteorite sites are in lower case letters. In the vicinity of Kellerberrin and Woolundra (upper middle of map), the Great Eastern Highway, the site of the former narrow gauge railway on which was Woolundra, and the present standard gauge railway line are within a few tens of metres of each other. Inset: Western Australia showing location of the map area.

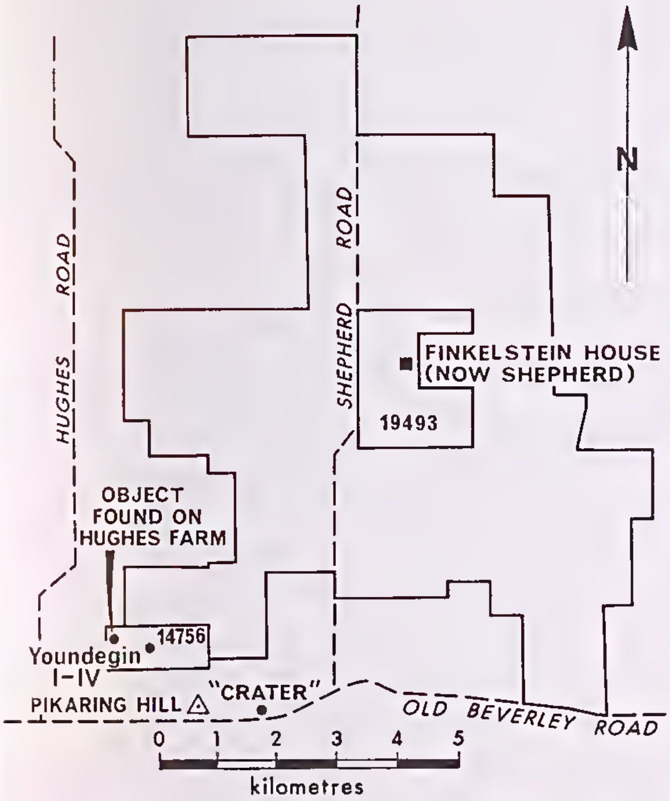

Figure 2 The southern group of 16 Locations held by members of the Finkelstein family in 1929. Only Locations 14 756 and 19 493 are shown individually.

the homestead block. The farm area held by the Finkelsteins in 1929 comprised 29 Locations (H J Murphy, pers comm). The southern locations alone (Fig. 2) had total area *c* 5 000 ha. It would have been a considerable coincidence if Youndegin VII had been found at the homestead or even on the homestead block, which we searched unsuccessfully. We regard the find site as being more probably an unknown point somewhere within Finkelstein's farm. One possibility would be Location 14 756, on which Youndegin I-IV were found 45 years earlier and a metallic object was found *c* 40 years later.

Youndegin VIII This collective name was given by Simpson (1938) to "many fragments in private hands" found by Knoop and others during the period 1891-1929 and said to aggregate *c* 14 kg. No find sites were recorded but the mention of Knoop and the range of dates suggest that these minor fragments were associated with Youndegin V, VI and VII.

Mount Stirling This mass was sold to the Australian Museum by Mr J F Connelly for £50 and entered in the Museum register on 5 April 1897 as "Meteorite from West Australia weighing 200 1/8 lbs" (90.8 kg). The locality was recorded as "nr Mount Stirling about 25 miles away in a SE direction . . . .". The following remarks were added: "Found on an open plain exposed on the surf. and surrounded by a considerable quant. of iron oxide which had scaled off. Existence known for at least five years". A further piece from the same locality weighing 0.42 kg was received at the Australian Museum later (Cooksey 1899).

Connelly was a life-long prospector (Erickson 1986). His site statement for a valuable asset must therefore be regarded with considerable caution. The statement is very rounded both in direction and distance. The locality could better have been referred to some much closer feature such as Mt Bebb, which is halfway between the stated site and Pikaring Hill and had already been named in 1897. Confusion between nearness and distance has caused some writers to place the find site at the mount itself (*eg* Woodward 1912) and *vice versa* (Eaton 1979).

Extensive enquiries by the authors at farmhouses within a sector centred on Mount Stirling and extending from Nornakin to Ardath (Fig. 1) produced no additional information. Connelly memorabilia and family letters were searched unsuccessfully by Ms K-J Connelly. The original statement has had to be accepted, though it may be intentionally vague as in the case of Youndegin V & VI, which were also sold by their finder.

Mooranoppin Mooranoppin I, of mass 1.1 kg, was brought in to Mr R B Leake of Mooranoppin farm by an aborigine, who had found it on the sandplain in the vicinity (Woodward 1896). Pikaring Hill, the focal point of previous finds, is 55 km S of the farm (Fig. 1). Subsequently, Woodward (1897, 1912) stated that the mass had been found in 1893 or before and left at Mr Massingham's. Massingham was Leake's neighbour on Milligan Station, a few kilometres NNW of Mooranoppin. Mooranoppin, unlike Milligan, was on the road to York (Fig. 1). In the geography of the early 1890s, an object from Milligan would almost certainly have passed via Mooranoppin en route to the Museum in Perth. Original incorrect attribution to Mooranoppin might thus have occurred. No doubts were expressed about a find site in this general vicinity until 45 years later, when Simpson (1938) referred to a site "somewhere to the south". Not all later writers (*eg* Glauert 1954) have accepted this change, for which the source of information was not stated. Mooranoppin II, of weight 0.82 kg, was reported by Simpson (1938) to have been brought to Mooranoppin farm about the same time and from the same place as Mooranoppin I, and to have been kept there until given to him by R Maitland Leake (son of R B Leake) about 1933, *c* 40 years after being found.

We found no evidence that the find site of Mooranoppin I & II was other than in the general area north of Kellerberrin (Fig. 1). The disposition of the Youndegin meteorites would therefore have been analogous to the Mundrabilla meteorites and the distant Tookana Rockhole recovery (de Laeter & Cleverly 1983). However, a curious coincidence was noted.

At some time prior to 1900, Louis Knoop, the finder of Youndegin V, VI and VIII (in part), established Knoop & Co, eucalyptus oil manufacturers and sandalwood merchants, with addresses in Fremantle and Woolundra (Anon c 1900). Woolundra was the first railway station east of Kellerberrin on the former 3′6″ railway line and was situated at the eastern boundary of Mooranoppin farm (Fig. 1). As a sandalwood merchant, Knoop would have had the heavy wagons necessary to transport loads of sandalwood (or meteorites) to be railed from his Woolundra depot. Thus Mooranoppin I & II, the only pieces of the Youndegin meteorite found far distant from the others, had been brought in to people who were the neighbour(s) of Louis Knoop.

Quairading (syn Youndegin IX) The heaviest member of the shower (2 626 kg) was re-discovered by Mr E C Johnson on Avon Location 23 656, where it was examined by Fimmell (1952). It had been found initially by Mr H Johnson in 1903 (letter dated 23 April 1953 on WAM file "Meteorites before 1963"). A few pieces of iron shale found by the authors near the SW corner of Avon Location 23 656 confirmed the find site as being nearly 6 km E of Wamenusking Sports Centre and 30 km in direction 121° from the town of Quairading (Fig. 1).

Youndegin iron, 4.66 kg A small un-named iron acquired by Quairading District High School before 1972 from an unrecorded source is a member of the Youndegin shower (de Laeter & Hosie 1985). The iron may have been received at the school about 1967 (E Martindale, pers comm).

Circumstantial evidence suggests that this iron could be the object found on Hughes' farm. There is, on the one hand, a dense metallic object, double-fist sized, found *c* 1968 and taken to Quairading, where it proved extremely resistant to cutting. There is, on the other hand, a Youndegin iron, 16 × 14 × 8 cm, of high hardness, acquired by Quairading District High School before 1972, perhaps in 1967. Mr C A Hughes is unable to confirm the identification with certainty, his recollections—now unsure—being of a more compact and redder object, but neither does he dismiss the identification as impossible.

Youndegin iron, 1.50 kg A small, unnamed iron registered in 1929 as No. 8629 in the collection of the Geology Department, University of Western Australia has been identified as a member of the Youndegin shower; two abortive attempts had been made to cut it (A W R Bevan pers comm).

Youndegin VII was found in 1929 (Simpson 1938) and this iron was acquired by the University in the same year. There are long time intervals in the sequence of finds both before and after that year. Conceivably, this iron could be a reason why Simpson (1938) defined Youndegin VIII as including fragments found up to 1929.

So-called "meteorite crater" A feature 1 km E of Pikaring Hill and 60 m north of Old Beverley Road is considered by some local people to be a meteorite crater (Fig. 2). The "crater" is 27 m diameter inclusive of the very low, washed-out, circumferential mound of displaced material. There is rather more than 1 m of relief from the granite exposed in the bottom of the pit to the top of the mound.

No meteoritic material or iron shale was found. The granite shows no evident shock or cataclastic effects. The only features suggestive of a crater are as follows. The smooth elevational profile of the mound is unlike excavated soaks such as that 0.5 km in direction 330° from Pikaring Hill, where spoil dumps are of the unequal size and spacing dictated by convenience of excavation. However, the smoothness may be a consequence of considerable age; the "crater" has been known since at least early in this century (J H Shepherd, pers comm). The site is an unlikely one for a soak (agreed by both local people and the authors). However, excavation may have been prompted by water seepage from the gaping joint now exposed in the bottom of the pit. Finally, there is the purely circumstantial evidence that the "crater" is within the 5 km circle enclosing the find sites of Youndegin I-VI and perhaps of several minor masses also. This suggests that the local farming community, who have no experience of a genuine meteorite crater, have some tradition of meteorite recoveries in the vicinity.

The "crater" is probably the one reported to the Western Australian Museum on an earlier occasion and regarded as a soak by G J H McCall (pers comm). It would therefore be the soak indicated by McCall & de Laeter (1965, Fig. 3).

Conclusions

The preferred find sites of the Youndegin meteorites are presented in Table 1. It is unlikely that precise sites will ever be known for some members of the shower. An attempted delineation of the strewnfield is shown in Fig. 1, from which it appears that the Youndegin meteoroid travelled W or somewhat S of W. It fragmented in the atmosphere to produce the Mount Stirling and Quairading meteorites and perhaps also a third mass which was secondarily fragmented to produce eventually the Youndegin I-VIII meteorites. Some of the smaller masses were detached from major masses as the result of prolonged weathering rather than by fragmentation in the atmosphere. The find site of the Mount Stirling meteorite is, at best, very approximate. Correction of this site could lead to a radical change in the form and orientation of the strewnfield. One or two small masses may have landed distantly and independently a few kilometres N of Kellerberrin.

Table 1

Find sites of Youndegin meteorites

Meteorite	Find site according to (a)[1] & (b)[2]	Find site (this paper)
Youndegin I-III	(a) & (b) 32°02′S, 117°35′E	32°05′S, 117°43′E
Youndegin IV	(a) 32°10′S, 118°50′E (b) 32°02′S, 117°35′E	32°05′S, 117°43′E
Youndegin V & VI	(a) & (b) 32°10′S, 118°50′E	Within 5 km of 32°05′S, 117°43′E
Youndegin VII	(a) & (b) 32°03′S, 118°46′E	Same as Youndegin I-IV (?
Youndegin VIII	—	Same as Youndegin V, VI and VII
Mount Stirling	(a) 31°58′S, 117°55′E (b) 32°06′S, 117°55′E	Perhaps very approx 32°05′S, 117°55′E
Mooranoppin I & II	(a) Approx 31°35′S, 117°46′E (b) 31°45′S, 117°45′E	General vicinity of 31°34′S, 117°44′E
Quairading	(a) & (b) 32°10′S, 117°42′E	32°09′S, 117°40′E
Youndegin iron, 4.66 kg	—	Same as Youndegin I-IV (?
Youndegin iron, 1.50 kg	—	Same as Youndegin VII (?

[1] McCall & de Laeter (1965)
[2] Buchwald (1975)

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Limnology of the southern acid peat flats, South-western Australia

B J Pusey[1] & D H Edward

Department of Zoology, The University of Western Australian, Nedlands, WA 6009
[1] Current address: Centre for Catchment & In-stream Research,
Division of Australian Environmental Studies, Griffith University, Nathan, Qld 4111

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Abstract

Temporal changes in water chemistry and invertebrate community composition, abundance and diversity were monitored for two years and one year, respectively, for aquatic habitats in an extensive area of coastal wetlands of South-western Australia. The locations sampled included permanent and temporary lotic and lentic environments. pH was low and declined to a minimum of 4.1 in winter. Water transparency was also low due to high levels of dissolved organic substances. A distinct effect of season on water chemistry was observed in contrast to changes reported for other small Australian ponds, temporary or otherwise. Significant temporal changes in the density, diversity and composition of the invertebrate fauna (zooplankton and zoobenthos) were recorded. Fish predation was potentially an important determinant of invertebrate diversity and community structure. Few of the insect fauna showed adaptations to ephemerality and fauna known to be associated with temporary waters were, in general, lacking. This is suggested to be due to the predictable seasonality of the climate which allows little distinction between temporary and permanent habitats for a highly seasonal fauna. Similarity of species composition between locations was low for insect fauna, reflecting the lack of specific drought survival mechanisms and the importance of opportunism and colonization ability. Assemblage similarity was greatest for the crustacean fauna and was attributed to a greater prevalence of drought survival mechanisms.

Introduction

The seasonal nature of much of Australia's rainfall has ensured that many aquatic habitats are temporary in nature. Limnological studies of Australian temporary water bodies have encompassed pools (Edward 1964, Jones 1974, 1975, Bayly 1982), ponds (Morton & Bayly 1977), streams (Towns 1985, Bunn *et al* 1986, Boulton & Suter 1986, Smith & Pearson 1987) and lakes (Bonython & Mason 1953, Maher 1984, Maher & Carpenter 1984). Notwithstanding the above, temporary waters are among the least studied of Australian standing waters (Bayly & Williams 1973).

Although the presence of temporary aquatic habitats is usually seasonally determined, this is less so for the variations in physico-chemical parameters. Ponds, temporary or otherwise, are said to be characterized by their high degree of physico-chemical and biological variability (Bayly & Williams 1973, Williams 1980). For example, Bayly & Williams (1973) suggest that seasonal patterns of oxygen concentration and pH in shallow ponds are absent or ill-defined. This was shown to be the case for fluctuations in conductivity in south-eastern Australian temporary ponds (Morton & Bayly 1977) and Timms (1967, 1970a, b) showed variation in total dissolved solids and major ions of a number of permanent ponds to be highly variable and related to aseasonal rainfall. Similarly, Towns (1985) and Smith & Pearson (1987) present data that show, for pools in temporary streams, that changes in water chemistry were erratic, showed no seasonality, and in the latter study, were most greatly influenced by unpredictable rainfall. Such a relationship between aseasonal variation in chemical parameters and rainfall is not unexpected for areas where the pattern and the amount of rainfall is unpredictable (McMahon 1982, Lake *et al* 1986). In contrast, a Western Australian temporary stream showed a distinct seasonal pattern of variation in all parameters measured (Bunn *et al* 1986). These authors stress the importance of the predictability and regular seasonality of the region's climate to stream water chemistry and macro-invertebrate community structure.

Some biological features of Australian temporary aquatic habitats have been detailed (*eg* Bayly & Williams 1973) but apply only in the general sense. They generally have fewer species than permanent ponds and temporary streams (Bunn *et al* 1986, Boulton & Suter 1986) and pools in intermittent streams (Towns 1985, Smith & Pearson 1987). Temporary waters are suggested to provide habitats where competition between species is of little importance in determining patterns of distribution because of insufficient time for completion of competitive exclusion (Bayly & Williams 1973, but see Morton & Bayly

1977). Differences in species richness and composition between areas are most likely a result of colonization probabilities and geographical proximity.

Our study investigated the limnology of a range of lotic and lentic temporary and permanent water bodies of the southern acid peat flats of South-western Australia. A major aim was to determine the importance of the reported seasonality of the climate (Bunn *et al* 1986) on the physical and chemical environment and invertebrate community.

Methods

Study area

The study area was located in the south-west of Western Australia (Fig. 1). This area has a Mediterranean climate with high winter rainfall and dry hot summers. Tall dense forests of karri (*Eucalyptus diversicolor*) and jarrah (*E. marginata*) are typical of the area. In coastal areas the forests give way to low-lying heath and sedgelands (Smith 1972). The transition from forest to heath may be dramatic, occurring over distances of less than 100m and corresponding to an abrupt change from red erosional soils to leached peaty sands of the Chudalup and Blackwater associations (McArthur & Clifton 1975).

The localities sampled in this study include a range of habitats from temporary to permanent pool (sites 2, 3, 8 & 9 and sites 1 & 6 respectively) and temporary to permanent stream (sites 5 & 4 respectively). Within the pool category, both sites 1 & 9 were drained by a temporary stream. Site 8 was fed by a short (200 m) shallow stream. The physical characteristics of the study sites are further described in Pusey & Edward (1990). Site numbers used in that report are maintained here. Temporary water sites contained water from late autumn to mid-summer. All sites were either located in broad shallow valleys of the southern acid peat flats (Christensen 1982) or fed by drainage from such areas.

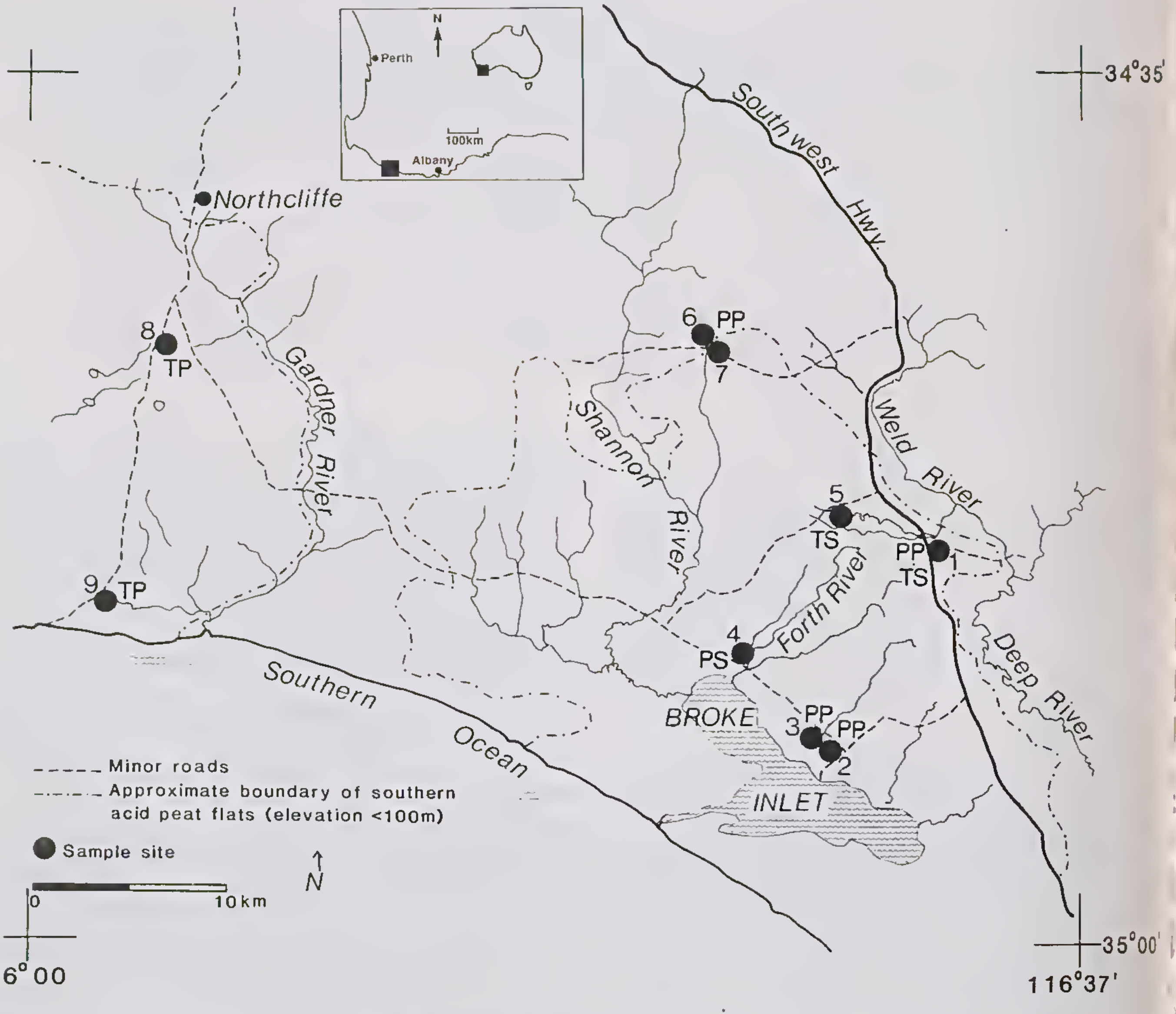

Figure 1 Location of the study sites and the approximate boundary of the southern acid peat flats. TP = temporary pool, TS = temporary stream, PP = permanent pool, PS = permanent stream.

Water chemistry

A single water sample was taken from the centre of each water body on each sampling occasion, immediately placed on ice and returned to the laboratory. Cation (Na^+, K^+, Ca^{2+} & Mg^{2+}) concentrations were determined by atomic absorption spectrophotometry (Varian AA475) and pH on a Chemtrix type 40 meter. Chloride ion concentrations were measured on a Buchler Cotlove (4-2000) chloridometer. Water temperatures were measured on each sampling occasion with a mercury thermometer. Dissolved oxygen concentrations were measured by a Delta Scientific model 1010 oxygen probe.

Optical clarity of the water was determined for four of the eight sites (1, 2, 4 & 6). Four replicate water samples were taken from each site in early June 1987 and kept on ice for 24 hours. A Secchi disc depth and one water sample were taken from the Deep River to provide a comparison as shallow water depths precluded the use of a Secchi disc at the study sites. Between 100 and 200 ml of each water sample were filtered through 0.45 um Millipore filters and the absorbance at 440nm of the filtrate determined in a Beckman Model 25 spectrophotometer and expressed as the G440 (*sensu* Kirk 1976).

Chlorophyll concentrations were determined for each of the four sites above by the method of Strickland and Parsons (1968) using a Beckman model spectrophotometer. Total chlorophyll concentration (a, b & c) was estimated from the absorption spectrum of the supernatant resulting from the analysis detailed above.

Substrate particle size distribution

Four replicate substrate cores (10 cm diameter, 10 cm deep) were taken from each site. Each core was dried at 30°C until a constant weight was obtained. Organic material was separated from the inorganic fraction by flotation. Both fractions were again dried to a constant weight and the mean organic content estimated. The organic component was divided into two fractions: coarse particulate organic matter (CPOM—particles of a diameter equal to or greater than 1 mm) and fine particulate organic matter (FPOM—particles of a diameter less than 1 mm). The size distribution of the inorganic particles was estimated by sieving through a series of graduated sieves (8, 4, 2, 1, 0.5 & 0.25 mm).

The invertebrate fauna

The invertebrate fauna was sampled at each of the 8 locations on 5 occasions: twice before the summer drought of 1985/86 (Sep & Nov 1985) and 3 times after the beginning of the winter wet period (June, Aug & Sep 1986). Sampling in 1986 resumed within 3 wks of inundation of the sites. Plankton was collected by straining 45 l of water through a 0.25 mm sieve and the retained animals preserved in 70% alcohol. Three replicates were taken from each site. Benthic invertebrates were sampled with a 10 cm diameter core sampler. Three 10 cm deep sediment cores were taken from each site and immediately preserved in 10% formalin. Benthic organisms and organic material were later floated away from the inorganic fraction by immersion in a concentrated $CaCl^2$ solution. Both planktonic and benthic fractions were sorted under a stereomicroscope at 12X. All animals, with the exception of nematodes, were enumerated and identified by matching against voucher specimens held in the Aquatic Research Laboratory, Department of Zoology, UWA. Abundances were expressed as the number of individuals . m^{-3} and m^{-2} for zooplankton and zoobenthos respectively.

Changes in abundance were assessed by a non-parametric two-way (site by time) analysis of variance by ranks. A non-parametric analysis was used because heteroscedasticity could not be reduced below significant levels by commonly employed transformations. Differences between means were tested with a non-parametric Tukey-type multiple comparisons test (Zar 1984: 199-201). Changes in diversity (estimated by the Shannon index) were analysed the same way. Categories used in the estimation of diversity are listed in the caption to Figure 6.

Results

Water chemistry

Ionic concentrations varied seasonally and peak concentrations were achieved in or just prior to summer when water volumes were at their minimum (Fig. 2). The concentration of dissolved salts was low at all sites and Na^+ was the dominant cation, usually followed by Mg^{2+}, Ca^{2+} and K^+. Except at site 9, K^+ was occasionally more concentrated than Ca^{2+} while at this site (9), Ca^{2+} was often more concentrated than Mg^{2+}. The mean (±SE) proportion of total measured cations contributed by Na^+ was high; 84.2 ± 1.2%.

H^+ concentration also varied seasonally with pH at its minimum in mid winter. Sites 2 & 3 were the least acidic and pH was never recorded below 5.0 at these sites. A minimum pH of 4.1 was recorded at Sites 5 & 8. No consistent relationship between Ca^{2+} and pH was apparent within any one site but sites with the highest pH tended to have elevated calcium concentrations (Sites 2, 3 & 9).

Oxygen concentration and water temperature also showed seasonal variation in magnitude. Similar temperatures was recorded for each site with maximum temperatures being recorded in or just prior to summer (Table 1). Maximum dissolved oxygen concentrations were recorded during the winter months when temperatures were at their lowest. Although dissolved oxygen was lowest in summer at no time was it observed to fall below 50% saturation.

Optical clarity varied between sites (Table 2). Site 1, with a G(440) of 3.58 m^{-1}, contained the darkest water and absorbance was equivalent to that of the Deep River where a Secchi disc depth of 1.1 m was recorded. Sites 3 and 6 had low absorbance values and were virtually colourless. Of the sites not sampled in this analysis, all except Site 2 were darkly stained and 'tea-coloured'. Chlorophyll (a, b & c) concentration was not negatively associated with water clarity as the highest concentration occurred in the darker water site (Table 2). Although planktonic algae were at low density at Site 3 it was noticed at the time of sampling that the substrate was covered by a fine mat of filamentous algae. This was also observed at Site 2 but at no other site during the period of study. Low chlorophyll concentrations were recorded from the running water site, Site 4.

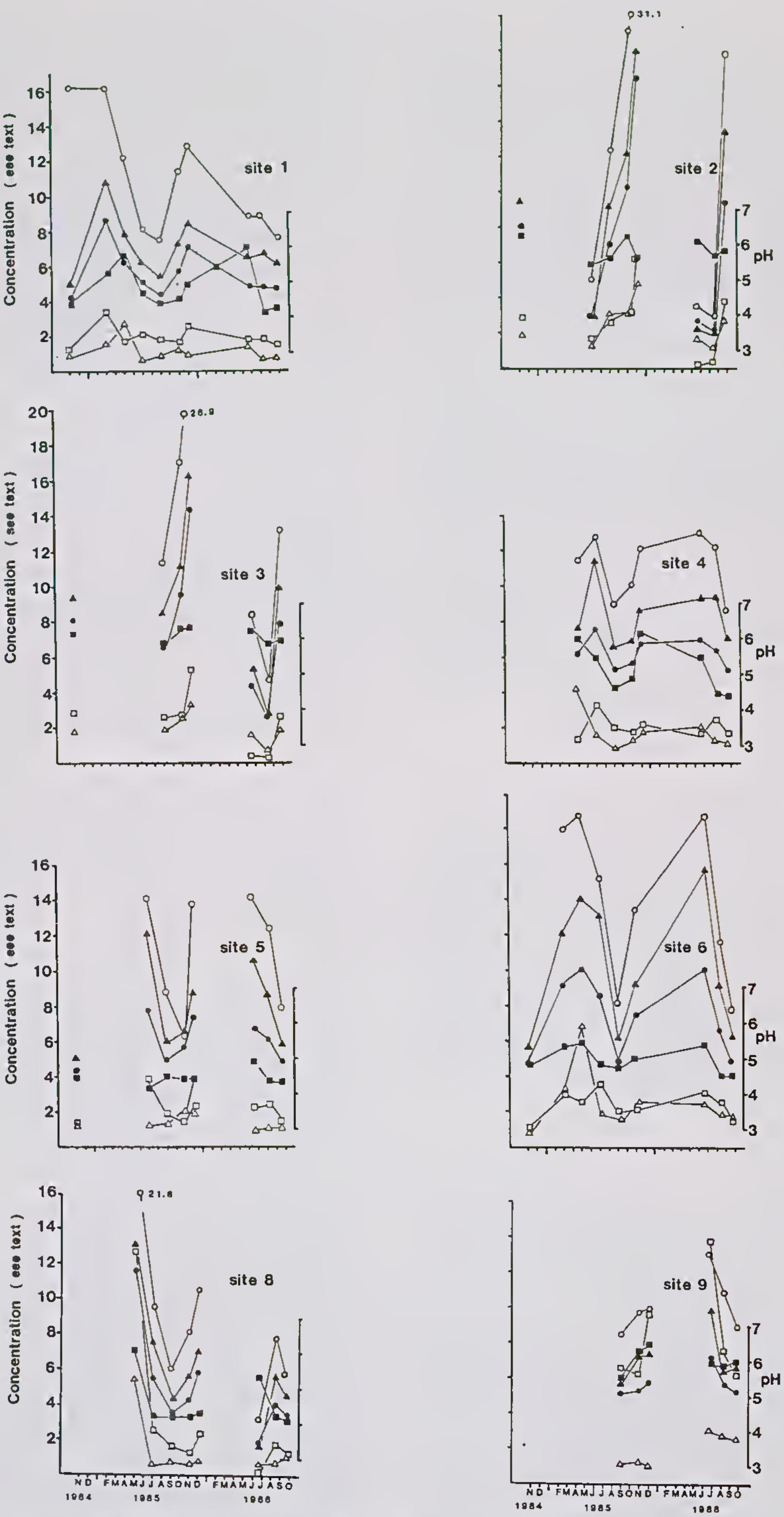

Figure 2 Temporal changes in the concentration of major ions and pH at each of the study sites. Concentrations ar given as ppm except for Na^{+} and Cl^{-} where concentrations are expressed as ppm X 10^{-1}. ○ = Cl^{-}, ● = Na^{+}, _ = Ca ■ = pH, △ = K^{+} and ▲ = Mg^{2+}

Table 1

Maxima and minima water temperatures and oxygen concentrations for each site. The month in which the measurement was made is given in parentheses. (- denotes no measurement was made).

Site	Temperature		Dissolved Oxygen Concentration (ppm)	
	Max	Min	Max	Min
1	25.2 (Dec)	7.6 (June)	8.4 (June)	5.9 (Dec)
2	24.0 (Nov)	10.2 (Aug)	10.0 (June)	7.9 (Nov)
3	25.8 (Nov)	8.0 (Sept)	10.0 (June)	—
4	23.5 (Feb)	9.7 (June)	8.8 (June)	7.7 (Dec)
5	25.0 (Nov)	11.6 (June)	—	5.2 (Dec)
6	22.0 (Feb)	5.1 (June)	8.0 (June)	5.6 (Nov)
8	26.0 (Nov)	13.0 (Aug)	—	8.1 (Dec)
9	28.0 (Nov)	12.0 (Aug)	—	8.0 (Dec)

Table 2

Gilvin absorption (G440) and chlorophyl concentration (a, b and c) (ugL^{-1}) at four of the study sites and the Deep River. The mean value and standard error are given with the number of replicates in parentheses.

Site	G440	Chlorophyll concentration
1	3.58±0.41 (4)	6.53±0.91 (4)
2	0.59±0.05 (4)	2.44±0.32 (3)
4	1.30±0.00 (4)	2.12±0.40 (4)
6	0.75±0.20 (4)	4.26±0.25 (3)
Deep River	3.60 (1)	4.44 (1)

Substrate particle size distribution

The organic content of the substrate differed between sites (Fig. 3). Sites 2, 3 & 4 contained very little organic matter with total organic content being less than 1% dry weight. Sites 1, 5, 8 & 9 all had a total organic content of between 1 and 5% dry weight. Site 6 had the greatest organic content, 38% dry weight. The contribution of CPOM to the total organic content was similar for all sites. The inorganic sediment was composed primarily of particles less than 1 mm diameter. Substrate particle size distribution appeared to be similar in all sites although this may be partly a reflection of the sieve sizes used; Sites 2 & 3 had clay-like substrates in contrast to the white sands of the other sites.

The invertebrate fauna

The mean density of zooplankton and benthos showed significant temporal variation during the period of study ($P < 0.01$ for both). Significant variation between sites was also detected ($P < 0.01$ and 0.001 respectively) (Table 3). Densities were generally higher in June, the beginning of the wet season (Fig. 4 and Table 4). The maximum zooplankton density occurred at Site 2 where a mean density of 38 000 individuals m^{-3} was recorded. High mean zoobenthos density (25 000 individuals m^{-2}) was recorded at this site and time also. High densities of zoobenthos were also recorded at Sites 4 & 6 where mean densities of 24 000 and 25 000 individuals m^{-2} were recorded, respectively (Fig. 3).

In general, zooplankton tended to be most abundant at the temporary pool sites (Sites 2, 3, 8 & 9) and least so at the two stream sites (Sites 4 & 5) and Site 6. Zoobenthos, however, showed no such pattern and between site differences in density were much less pronounced (Table 4).

Significant temporal variation in the diversity of zooplankton and zoobenthos was also detected ($P < 0.01$ and 0.05 respectively, Table 3). In general the trend was for diversity to be lowest when densities were highest (Figs 4 & 5). Zooplankton, but not zoobenthos, diversity varied significantly between locations. Changes in the density of the two calanoid copepods appeared to be the major determinant of changes in zooplankton diversity and density (Fig. 6) at temporary pool and temporary stream/pool sites (1, 2, 3, 8 & 9). Calanoid density usually decreased toward summer except at Site 3 in 1986. Zooplankton, in general, were a very minor component of the fauna at Site 4 and comprised only about 3% of the total number of individuals. In contrast, site 5, also a lotic habitat, showed a much greater contribution by plank-

Table 3

H values and their associated levels of significance for two way ANOVAs by ranks for density and diversity of zooplankton and zoobenthos. (ns - $P > 0.05$, ** $P < 0.01$, *** $P < 0.001$).

Variable	Component	Source of variation	df	H	P
Density	Zooplankton	Site	7	21.9	**
		Time	4	14.4	**
		Site X Time	28	26.6	ns
	Zoobenthos	Site	7	25.0	***
		Time	4	14.1	**
		Site X Time	28	31.2	ns
Diversity	Zooplankton	Site	7	24.3	***
		Time	4	14.0	**
		Site X Time	28	18.7	ns
	Zoobenthos	Site	7	12.2	ns
		Time	4	10.6	*
		Site X Time	28	38.8	ns

Table 4

Betweem site and season differences in density and diversity of zooplankton and benthos. Highest to lowest values are arrayed from left to right. Mean values not significantly diferrent from another ($P < 0.05$) are joined by a solid line.

Variable	Component	Factor	
Density	Zooplankton	Site	3 2 9 1 8 5 6 4
		Time	J A S86 N S85
	Zoobenthos	Site	6 4 3 8 2 9 5 1
		Time	J A S86 N S85
Diversity	Zooplankton	Site	9 5 6 8 4 1 2 3
		Time	S85 S86 A J N
	Zoobenthos	Time	S86 N A S85 J

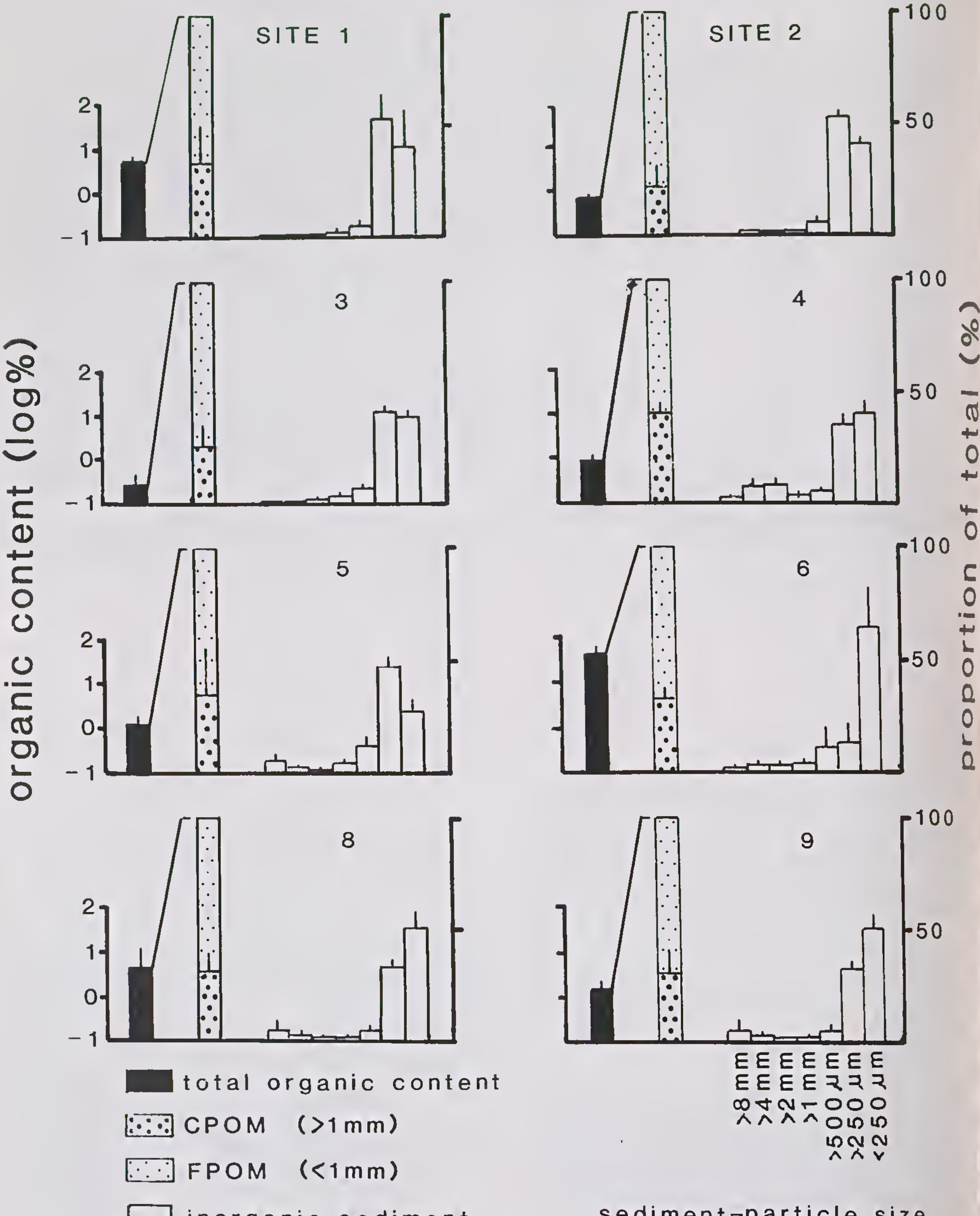

Figure 3 Proportion of organic sediment to the total sediment, the composition of organic sediment and the size distribution of inorganic sediment particles. (Note that the left hand axis is a log scale. CPOM and FPOM are coarse and fine particulate organic matter respectively. The mean and standard error of the mean from four replicate samples are shown.)

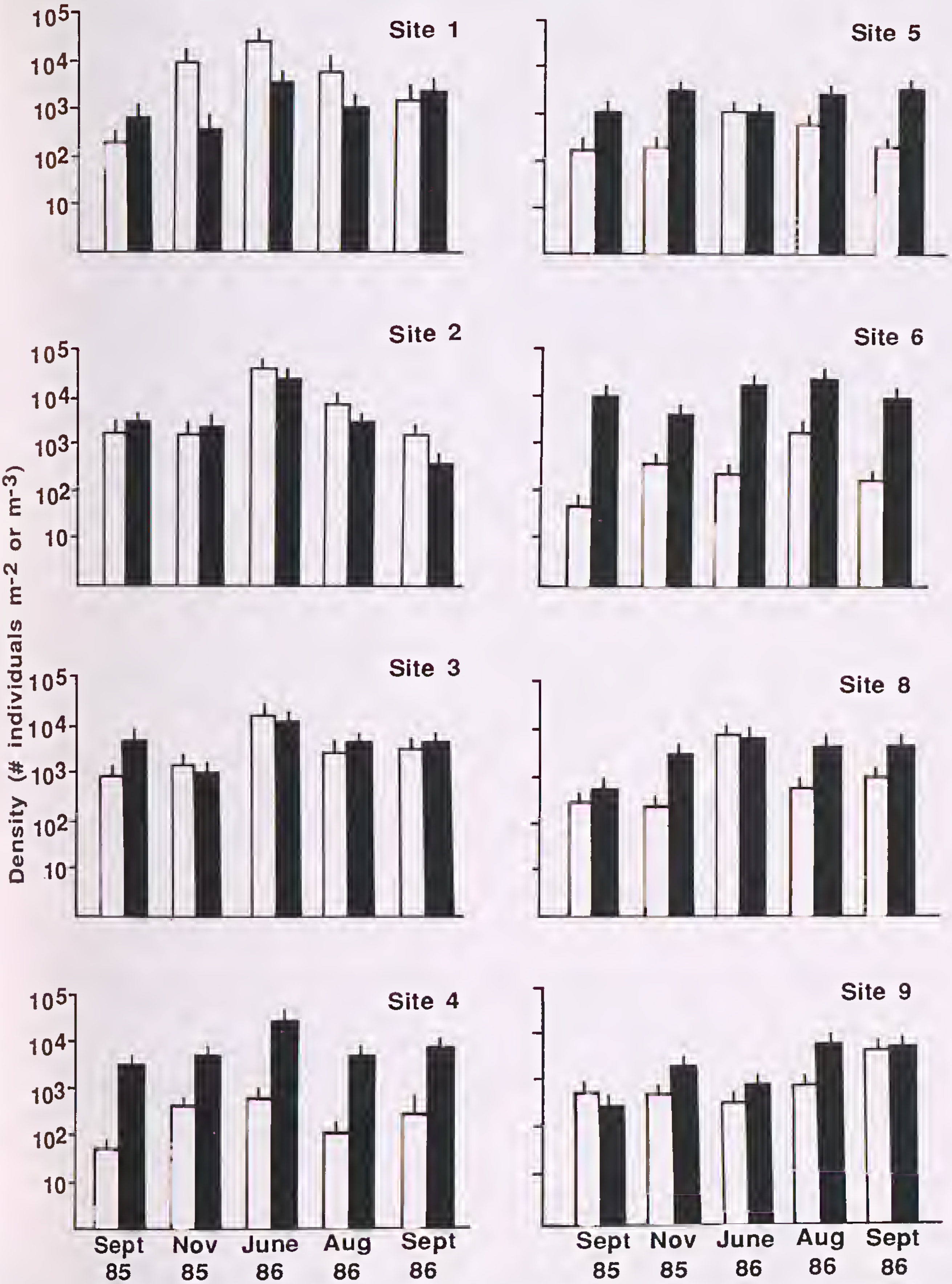

Figure 4 Temporal changes in the density of zooplankton and zoobenthos at each site during the study period. (Density is expressed as the number of individuals per cubic and squared metre respectively. The mean and SEM for three replicates are shown. Zooplankton is represented by the open bars and zoobenthos by the solid bars.)

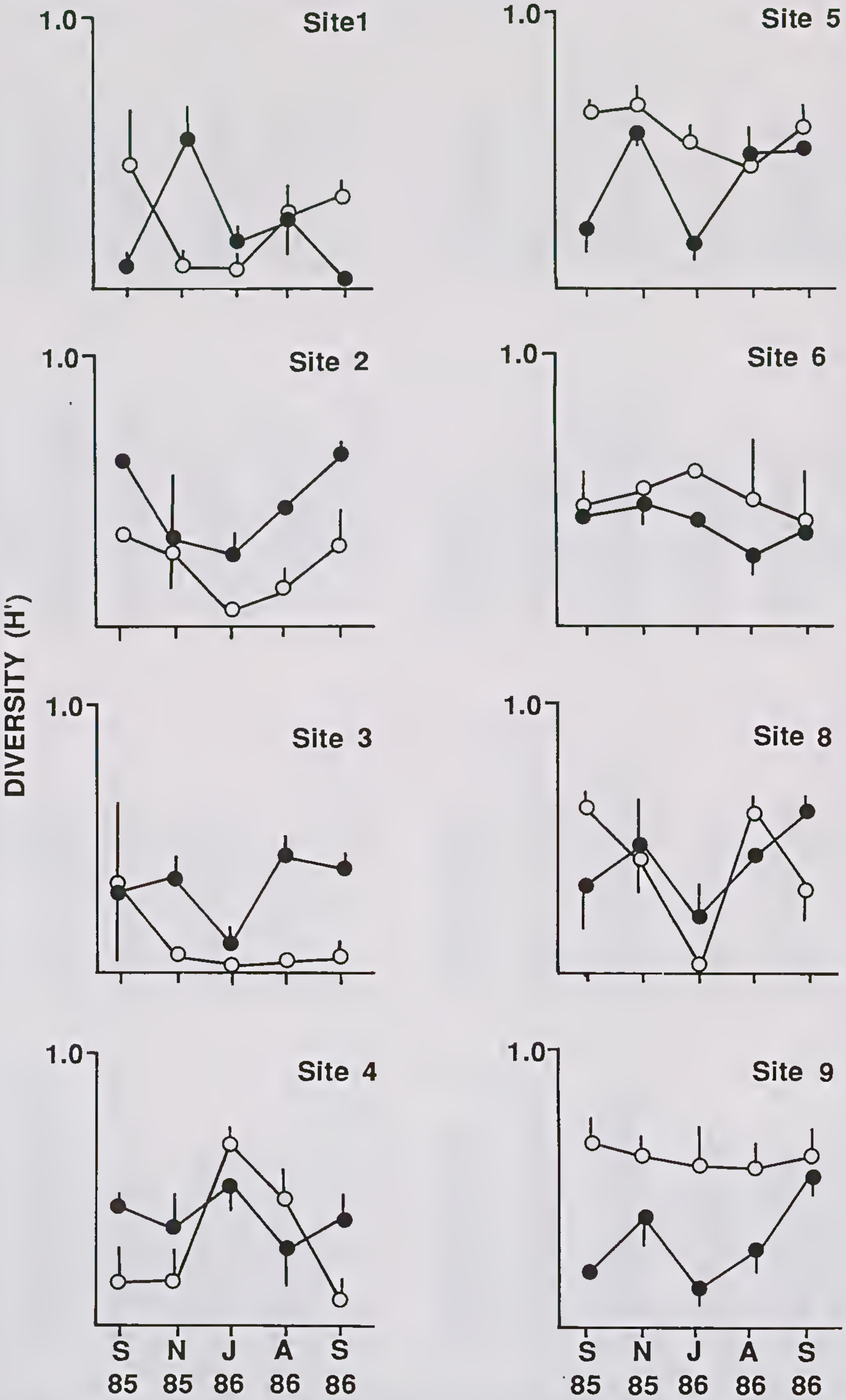

Figure 5 Temporal changes in diversity of zooplankton and zoobenthos at each site during the study period. (Mean & SE are shown. Shading is as in Fig. 4)

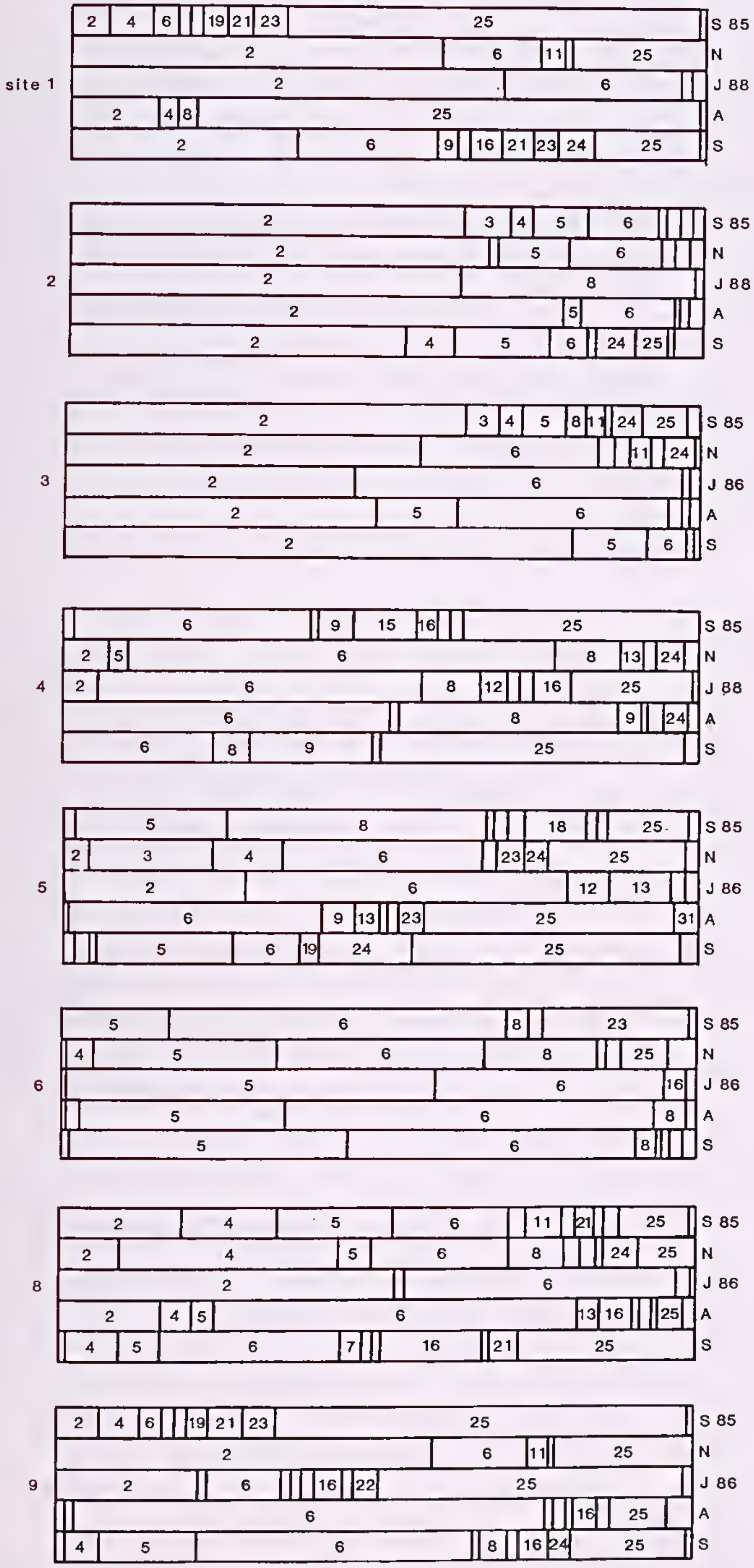

Figure 6 Temporal changes in the composition of the invertebrate fauna at each site. (Key to taxon code—2 Calanoidea 3 Harpacticoidea 4 Cladocera 5 Ostracoda 6 Chironomidae larvae 7 Chironomidae pupae 8 Ceratopogonidae larvae 9 Simulidae larvae 10 Diptera adults 11 Coleoptera larvae 12 aquatic Coleoptera 13 Collembola 15 Plecoptera and Ephemeroptera 16 trichoptera 18 aquatic Hemiptera 19 other aquatic insect larvae 21 other terrestrial insects 23 Hydracarina 24 Amphipoda and Isopoda 25 Oligochaeta)

Table 5

Total number of taxa and number of taxa within major taxon groups present at each site.

	Total	Site							
		1	2	3	4	5	6	8	9
Total	135	42	41	40	58	44	46	43	50
Arachnida	11	0	2	1	0	4	6	0	5
Crustacea	26	12	17	16	9	14	10	14	11
Ostracoda	10	1	6	5	2	3	2	3	2
Copepoda	4	3	3	3	3	3	3	3	3
Cladocera	5	5	4	4	3	2	3	5	3
Insecta	94	30	28	22	47	25	28	28	34
Trichoptera	17	3	1	2	5	4	7	3	6
Coleoptera	12	1	7	5	2	3	2	3	2
Diptera	52	20	12	11	31	15	15	16	22
Chironomidae	38	17	10	9	23	10	12	16	17
Tanypodinae	5	3	4	1	3	0	4	4	2
Orthocladiinae	13	5	0	1	9	5	2	4	6
Chironominae	18	8	6	7	10	5	6	8	9
Aphroteniinae	2	1	0	0	1	0	0	0	0

tonic organisms, especially ostracods, to the total abundance. The stream at this site is much more intimately associated with the peat flats which form vast shallow areas of inundated sedgelands and from which nearly all the discharge of Site 5 originates. The flats undoubtably contribute to the fauna of the stream.

Chironomid larva were an important component of the benthos at all sites except Site 1 and to a lesser extent Site 9 (Fig. 6). This group contributed greatly to the overall benthic density and changes in the density of chironomid larvae were largely responsible for observed seasonal changes in benthic density and diversity. The subfamily Chironominae numerically dominated the midge larva fauna of the pool sites (1, 2, 3, 6, 8 & 9) whilst the subfamily Orthocladiinae contributed greatest to abundance at stream sites (4 & 5) (Table 5 and Fig. 7). Those pool sites that were fed or drained by temporary streams also contained orthoclad larvae. In most cases, one species of chironomid larva was responsible for the majority of the total number of larvae present at a site at any given time (Fig. 7). At temporary pool sites 1, 2, 3 & 8, the dominant species was usually *Tanytarsus* sp 1. This species was also present at Site 9 where *Riethia* sp was also important. At the permanent pool site, Site 6, *Cladopelma curtivalva* was the numerically dominant species although the tanypod, *Procladius* sp. was also common. *Stictocladius uniserialis*, an orthoclad, was the most abundant species at Site 4 and was also present at Site 5 but at lower densities. Diversity at Site 5 tended to be high and no single species was numerically dominant over the entire study period. Orthocladiinae tended to be the most abundant especially during periods of maximum flow. In November, when water levels were receding and flow decreasing larvae of the Chironominae were numerically important. The persistence of the composition of midge larval assemblages was low as almost 40% of all major (those contributing 5% or more to the total) species/site associations occurred in one of the two years. The majority of those Chironomidae larvae achieving high densities could be assigned to the collector/gatherer trophic group and few scrapers or shredders were present (Table 6).

Of the 135 invertebrate taxa collected from the eight sites (Table 5 & Appendix 1) almost 70% were insects. The mean (± SE) proportion of insect taxa for temporary water

Table 6

Trophic status of major Chironomidae genera.

Only those species contibuting >5% of the total number of individuals at any one site and time are included. Trophic status has been assigned according to Merrit & Cummins (1977) and Edward (unpublished data). The number of species within genera recorded in this study is listed in parentheses.

Species	Collector	Filter feeder	Scraper	Shredder	Predator
Tanypodinae					
Procladius					+
Ablabesmyia					+
Orthocladiinae					
Stictocladius(2)	+				
Thienemanniella	+				
Limnophyes	+				
Parakiefferiella	+				
Orthocladiinae sp (3)	+				
Chironominae					
Cryptochironomus	+				+
Dicrotendipes (2)	+		+		
Cladopelma	+				+
Polypedilum	+			+	
Riethia	+			+?	
Tanytarsus (2)	+				
Rheotanytarsus	+	+			

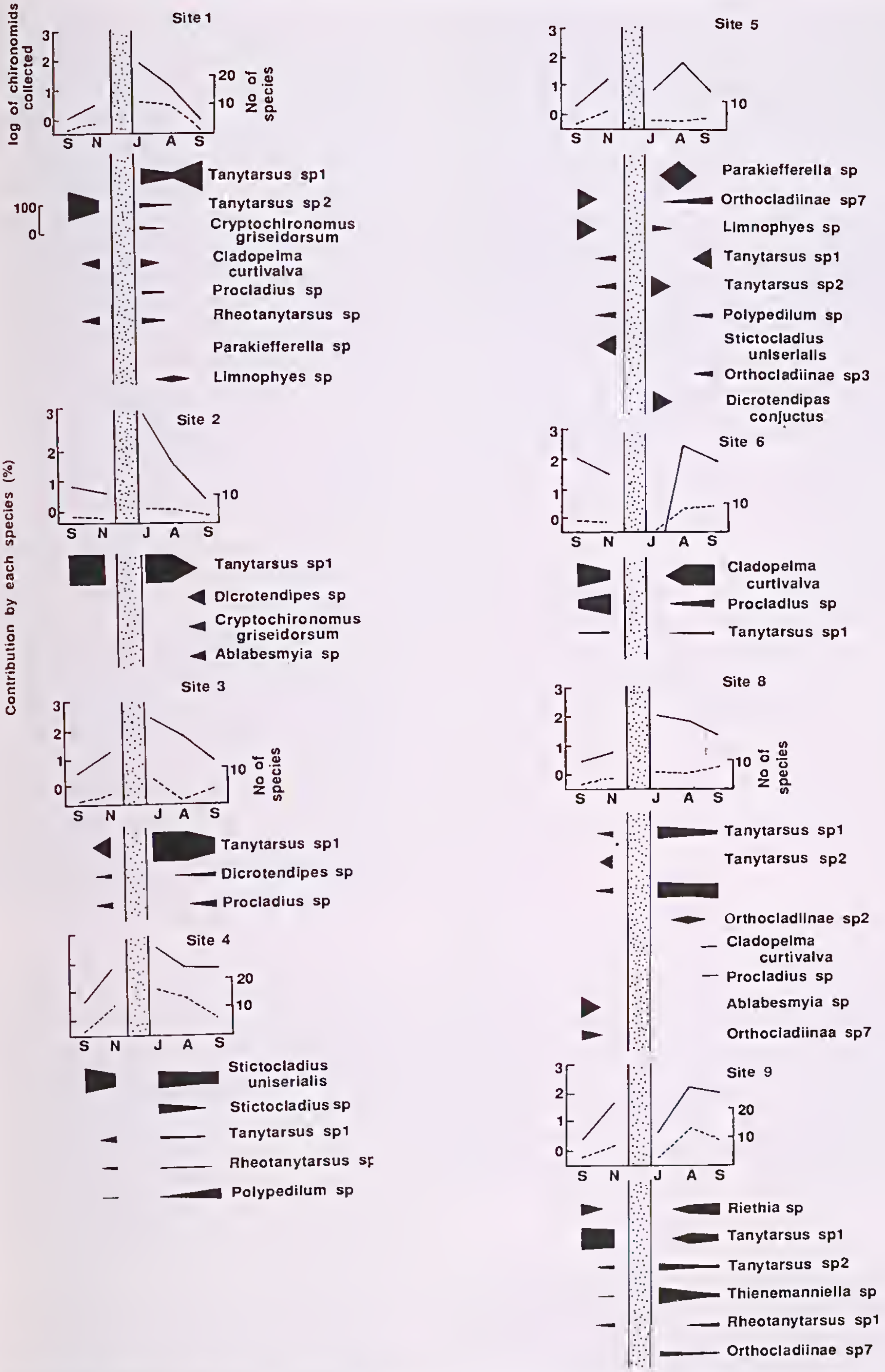

Figure 7 Temporal changes in species richness, abundance and proportional contribution of major species of chironomid larvae at each site.

sites was 64.3%. Site 4 contained a higher proportion of insect taxa (81%); this was not due solely to a paucity of planktonic crustacea (see above) for the number of insect taxa at this site was elevated above all other sites. This site contained the largest number of species of all sites. There was no overall tendency for permanent water sites to have greater numbers of species despite Site 4 having the greatest species richness. For example, Site 6 (a permanent pool) had fewer species than Site 9 and only marginally greater numbers of species than the site with the fewest species (Site 3). If water mites are excluded then differences between pool sites become even less pronounced. The major difference in species number was between permanent and temporary streams (Sites 4 & 5). These streams also shared few species.

Table 7

Between site similarities of species composition determined by Jaccard coefficients. Data listed are the similarity coefficients for the entire fauna, the crustacean fauna and the insect fauna respectively.

			Site				
1	2	3	4	5	6	8	9
—	0.36 0.45 0.26	0.36 0.47 0.27	0.31 0.50 0.31	0.32 0.44 0.41	0 27 0.57 0.23	0.39 0.62 0.41	0.39 0.44 0.42
2	—	0.58 0.83 0.28	0.21 0.44 0.12	0.20 0.29 0.15	0.26 0.35 0.24	0.33 0.55 0.22	0.28 0.47 0.19
3		—	0.22 0.47 0.17	0.29 0.42 0.20	0.25 0.30 0.22	0.36 0.58 0.28	0.29 0.42 0.20
4			—	0.21 0.27 0.20	0.22 0.36 0.21	0.29 0.53 0.23	0.37 0.53 0.35
5				—	0.24 0.14 0.18	0.28 0.33 0.23	0.31 0.25 0.31
6					—	0.25 0.33 0.30	0.33 0.40 0.29
8						—	0.35 0.47 0.32

Assemblage similarity, based on presence of shared species, was low for most site comparisons for both the total fauna and the insect fauna (Table 7). Comparisons of crustacean fauna, however, showed a greater similarity especially between sites of close proximity (Sites 2 & 3). Fifty two percent of the insect species collected from the southern acid peat flats have also been collected from lotic waters of the northern jarrah forest (Appendix 1).

Discussion

Water chemistry

Bayly (1964) suggested, on the basis of the distribution of the calanoid copepod, *Calamoecia tasmanica*, that an extensive area of coastal lowland of the southern half of the Australian continent, originally defined by Coaldrake (1961), may have a limnological as well as botanical unity. Bayly (1964) showed that, like many Australian waters, including those of south-western Australia (Williams & Buckney 1976), the proportions of dissolved ions were more similar to those of seawater than world average freshwater. Sites included in this report also showed, on average, this same ratio of major cations but with a slightly increased dominance by sodium ions. Salinities recorded in the present study are higher than that recorded by Bayly (1964) for dune lakes but much lower than reported for the majority of Western Australian rivers and lakes by Williams & Buckney (1976). It is generally accepted that rainwater salts are derived from the sea and that this source may contribute substantially to coastal freshwaters (Hart & McKelvie 1986). Accumulation of salts during the drying phase of the ephemeral waters of the flats plus an annual delivery via rainfall causes the slight salinization noted here.

The seasonal pattern of change in ionic concentrations is predominantly attributable to the seasonality of the rainfall. Minimum concentrations occur at a time of maximum rainfall and increased concentrations toward summer are associated with reduced rainfall and increased evaporation (Pusey & Edward in press). High concentrations at the beginning of the winter appear not to be related to rainfall *per se* but perhaps rather to elevation of the water table and dissolved salts within the ground water. Substantial dilution by subsequent rainfall would result in the seasonal decrease in salinity observed here. Seasonal variations in dissolved oxygen, temperature and the concentration of major ions, similar to that reported here, also occur in temporary and permanent headwater streams of the northern jarrah forest of south-western Australia (Bunn *et al* 1986). A major difference between the water chemistry of the two areas, however, concerns the timing of fluctuations in pH. Bunn *et al* (1986) found pH to be at its minimum in summer corresponding to periods of reduced flow and peak input and leaching of organic substances from *Eucalyptus* leaf litter. These leached organic compounds are the most likely substances contributing to the acidity of these streams at this time (Bunn pers comm). This contrasts with a late winter low in the study area. A winter low in pH was also recorded in two acidic dune lakes of south-eastern Queensland (Outridge *et al* 1989).

Bayly (1964) considered that in dune lakes, in the absence of appreciable amounts of bicarbonate, organic acids leached from the peaty substrate contribute substantially to acidity. Similarly, the underlying peat may contribute significantly to acidity in the southern acid peat flats. Leaching of organic compounds from submerged leaf litter would also appear to be an important source of acidity. Prolonged inundation, low flows and the flat terrain of the sedgelands would tend to favour the release and retention of such substances. Moreover, as the extent of inundation is determined by rainfall and is hence seasonal in nature, delivery of organic compounds would peak when maximum inudation occurred thus resulting in a late winter low of pH. Because leaching is a rapid process further rainfall would tend to dilute and increase pH.

Similarities in water transparency also exist between the dune lakes of south-eastern Queensland and the waters studied here. Dark stained waters, due to the presence of dissolved organic compounds, are characteristic of "perched" dune lakes and also of coastal streams and swamps of the "wallum" belt of the mainland coastal area

(Endler, Pusey & Arthington unpubl data). The darkest waters of the southern acid peat flats are comparable to the upper limits of G440 determined for Australian waters and tabulated by Kirk (1986) and Bowling (1988) but much lower than recently reported values for some Western Australian wetlands (Wrigley *et al* 1988). It is interesting to note that sites 2 & 3, although similar in many respects to the other sites, have very clear water with low concentrations of dissolved organic compounds. Moreover, these sites have the highest pH of all the sites examined. The more claylike nature of the substrates of these sites may provide an impervious barrier to the transport of organic substances into the water column from the underlying peat, or, peat substrates may be lacking from the soil profile of this particular area. These sites are not fed by streams and the water contained in the pools is a result of direct precipitation (which is retained because of the claylike soil) until maximum inundation of the flats. Only at this time do these sites receive water from the flats. This may explain the erratic changes in ion concentrations at these two sites.

Despite water transparency being greater at site 2, chlorophyll concentrations were not also correspondingly higher as would be expected if light transmittance were a limiting factor for phytoplankton production. Kirk (1986) suggests that this would normally be the case in all but the shallowest waters. All the sites examined here were shallow (< 2 m) and chorophyll a concentrations were comparable to concentrations recorded in dune lakes (Outridge *et al* 1989) where water transparency may be double that recorded here. Nutrient availability, rather than light, may be responsible for the differences between sites in chlorophyl concentrations. (Site 4, a moderately fast flowing stream, may be an exception as high phytoplankton abundances are not to be expected for lotic environments.) The observation of filamentous algae associated with the substrates of Sites 2 & 3 at a time when phytoplankton densities were low, suggests that nutrients may be limited in the water column because of an interaction between nutrients and inorganic sediments. Barclay (1966) noted that the presence of filamentous alga in a temporary pond occurred only when the pond first filled.

Invertebrate fauna

Many of the common species of microcrustacean fauna recorded here occur in many lentic habitats throughout Australia. *Calamoecia tasmanica* has been recorded from many coastal low altitude freshwater habitats especially those of low salinity and pH (Bayly 1964, 1979, Timms 1970a). Similarly, *Macrocyclops albidus* has also been recorded in eastern Australia (Timms 1967, 1969, 1970a). Cladoceran species recorded from the southern acid peat flats which also show a wide distribution include *Alona affinis* (Shiel 1976, Mitchell & Williams 1982), *Chydorus cf sphaericus* (Morton & Bayly 1977, Shiel 1976, Timms 1967, 1970a, Mitchell & Williams 1982) and *Neothrix armata* (Morton & Bayly 1977, Bayly 1982). It should be noted that *N.armata* and members of the above two genera have all been reared from samples of dry mud (Gurney 1927).

Bayly (1979) recorded the presence of an additional calanoid copepod from waters of the southern acid peat flats. This species, *Calamoecia elongata*, was said to be positively associated with temporary waters and as such must have some mechanism of drought survival. Such adaptations may also be shared by *C. attenuata* and *C.tasmanica* for they were found in association with temporary waters also and were present shortly after inundation and dominated the planktonic fauna for much of the wet season. Both these species produce large numbers of drought resistant eggs (Pusey unpublished data) and this undoubtably accounts for their dominance early in the wet season.

As many of the Ostracoda could be identified only to genus, little can be said about the extent of distribution of each species. However, many of the genera recorded are very widespread (Timms 1970a, b, Shiel 1976; Towns 1985; Bunn *et al* 1986). Members of the genera *Ilyodromus* and *Cypretta* are known to be associated with temporary waters (Barclay 1966, Bayly 1982) and one species *Cypretta baylyi* has been recorded from temporary pools of the southern acid peat flats (Bayly pers comm).

It should be emphasized that included in the unpublished data of Bayly (pers comm) for temporary pools in the general vicinity of the present study area are 6 calanoid and 5 cyclopoid Copepoda, 5 Ostracoda and 13 Cladocera of which only 2, 1, 2 (both tentative) and 2 respectively were recorded in this study. Although this study shows relatively high similarity in the composition of each location's microcrustacean assemblage, Bayly's data indicate that there is still considerable heterogeneity between pools.

Despite having widespread distributions, the insect fauna shows less similarity between sites than does the crustacean fauna. This difference is likely a result of the difference in drought survival mechanisms employed by the two groups. Insects, relying on annual recolonization, would tend to show patchy distributions resulting in dissimilar assemblage structure. The Crustacea, in contrast, appear to depend more on drought survival as eggs and thus ensure the continued presence of species between years. Any colonization that might occur would only tend to increase similarity.

Many of the species of Chironomidae, particularly the common species, also have distributions that encompass both south-western and eastern Australia. Several common lentic species with Australia wide distributions and including a number recorded for the southern acid peat flats are known to be opportunistic and colonize a variety of habitats (Edward 1986). Maher & Carpenter (1984) record that several genera and a number of species recorded in the present study were also important components of the benthic fauna of seasonally flooded Murrumbidgil Swamp and Lake Merrimajeel in New South Wales and described them as opportunists. Edward (1986) suggests that opportunism is common in the Chironomidae and that few species, with the exception of members of the genera *Paraborniella* and *Allotrissocladius* (Jones 1975), have drought survival mechanisms.

The only non-crustacean species recorded in the present study that is known to be positively associated with temporary waters is the snail *Glacidorbis occidentalis* (Bunn *et al* 1986). Conspicuously absent from the fauna were species of the crustacean order Anostraca and suborder Conchostraca, both of which are characteristic of temporary waters (Bayly & Williams 1973). Many of the insect species recorded here are present in permanent streams and rivers of the northern jarrah forest (see Appendix 1) and it appears that few are especially adapted to temporary waters. It seems more probable that an adaption to the seasonality of rainfall allows these species to colonize temporary waters as if there was little distinction between temporary and permanent waters at this time of the year. In view of this high overlap in species composition it is not unreasonable to suggest that many of the species recorded here and in jarrah forest streams will also occur in streams of the karri forests. It should be noted that the Trichopteran family Philoreithridae, absent from the northern jarrah forest (Bunn & Davies 1989) was present in the southern acid peat flats.

Zooplankton densities, when at their maximum, are comparable to other natural lentic systems, notwithstanding the differences in methods of collection (*eg* Shiel 1976). They were, however, never as high as those recorded for enriched systems (Mitchell & Williams 1982). The densities of zoobenthos recorded in the present study are almost an order of magnitude higher than densities recorded in headwater streams of the northern jarrah forest (Bunn *et al* 1986).

The decrease in zooplankton and zoobenthos abundance, due mainly to declines in abundandance of *Calamoecia* spp. and chironomid larvae, that occurs with increasing pond age corresponds to invasion of these temporary systems by small fish which utilize the southern acid peat flats for spawning (Pusey & Edward 1990). Several studies have shown that fish predation may affect both zooplankton (Geddes 1986, Vanni 1986, Bendall & McNicol 1987, Post & McQueen 1987) and zoobenthic communities (Gilinsky 1984). No fish were recorded from Site 3 in 1986 (Pusey & Edward 1990) and in that year plankton abundance did not decline as markedly with time as at other sites, especially the structurally and chemically similar site 2. Moreover, of all the sites at which *Calamoecia* spp were present, Site 3 was the only one to show an increase in the proportion of these species with increasing age of the pond. *Calamoecia* spp figure prominantly in the diets of all the fish species present on the southern acid peat flats (Pusey unpubl data).

High insolation and shallow water depths apparently allow sufficient light penetration to support algal production despite low transmittance. This may be important in maintaining both the planktonic and benthic community especially where the low organic content of the substrate would seem to preclude its importance as a significant source of organic carbon *ie* sites 2 & 3. At sites fed by drainage from the flats, allochthonous input of carbon may be substantial. Given the slight discharge over these areas sufficient time for significant processing by invertebrate shredders may occur. Leaf litter, even after some initial fragmentation (which is unlikely in such low velocity environments), would tend to remain *in situ* until processing by invertebrates was well advanced, at which time only small particles would be removed from the flats by drainage. If this were so then most particulate organic carbon entering streams and ponds would be of the fine fraction. This may explain the low trophic diversity observed for the Chironomidae. Trophic diversity may be higher on the flats themselves because of the probable presence of shredders and because autotrophy may be substantial in shallow areas (Meyer 1986).

Species richness data presented here support the contention that permanent waters have a greater species richness than do temporary waters but also suggests that this effect was limited to the permanent lotic system. Given that major seasonal changes in fauna can occur in streams of south-western Australia (Bunn *et al* 1986) and that permanent waters were sampled during the winter only, the differences in species richness may potentially be higher and apply to permanent pools also.

The number of taxa at any one site is comparable to that of pools and temporary streams of South Australia (Towns 1985) and northern Queensland (Smith & Pearson 1987). These latter authors suggest that species richness in northern Queensland temporary pools is higher than that of temperate regions. As species richness for temporary waters of the present study is greater than that of Smith & Pearson (1987) (104 *vs* 78) doubt is cast on this suggestion. Moreover, the original proposition was based on a comparison with Towns (1977) and there exists a large difference in the number of pools examined by each. As Smith & Pearson (1987) showed that species composition varied greatly between pools, as in this study, the number of pools examined will therefore greatly influence the estimation of overall species richness. It has been suggested that high heterogeneity of species composition in ponds and other small water bodies reflects the highly individual nature of these habitats (Friday 1987). An alternative explanation for the ponds and streams studied here is that differences in the probability of colonization are the main cause of such heterogeneity. This may especially be the case where the habitats as in the present study form a relatively homogenous group with respect to water chemistry and substrate composition.

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Appendix 1

Systematic list of taxa of invertebrates collected from the southern acid peat flats and the study sites in which they were present. An asterisk indicates whether a species is also present in streams and rivers of the northern jarrah forest (Bunn *et al* 1986, Edward unpubl data). Voucher numbers (Aquatic Research Laboratory, UWA) are only included for chironomid larvae identified to family or genera.

Taxon	Site							
	1	2	3	4	5	6	8	9
Mollusca								
*Glacidorbis occidentalis**					X			
*Ferrissia pettardi**						X		
Physastra sp								X
Annelida								
Oligochaete	X	X	X	X	X	X	X	X
Arachnida								
Oribatida sp 1		X			X	X		
Oribatida sp 2								X
Oribatida sp 3					X	X		X
Bdellidae sp					X			
Mesostigmata sp					X			
undescribed species and genera						X		X
Limnesia sp		X	X					
Oxus sp						X		X
Arrenurus sp								X
Coaustraliobates sp						X		
Koenikea sp						X		
Crustacea								
Ostracoda								
Ilyodromus sp 1	X					X		
Ilyodromus sp 2		X	X				X	
Ilyodromus sp 3		X	X					
Ilyodromus sp 4							X	
Gomphodella sp		X	X			X		
Cypretta sp		X	X	X				X
Newhamia sp		X						
Limnocythere mowbrayensis		X	X	X	X		X	X
Limnocythere sp					X			
undescribed genera					X			
Copepoda								
Harpacticoidea sp 1	X	X	X		X	X	X	X
Calanoidea								
*Calamoecia (attenuata & tasmanica)**	X	X	X	X	X		X	X
Cyclopoidea								
*Macrocyclops albidus**	X			X		X		
Metacyclops sp (*cf arnaudi*)	X	X	X	X	X	X	X	X
Cladocera								
Alona (=Biapertura) affinis	X	X	X	X		X	X	X
Echinisca sp (*cf capensis*)	X	X		X		X	X	X
Neothrix armata	X	X	X		X		X	
Simocephalus acutirostratus	X		X	X	X		X	
Chydorus sp	X	X	X			X	X	X
Isopoda								
Phreatoicoidea								
Amphisopus ?lintoni		X	X		X			
A. ?annectans					X			
Amphipoda								
*Perthia acutitelson**						X		
Perthia sp 1		X	X	X			X	
Perthia sp 2	X	X	X	X			X	
undescribed genera					X			
Decapoda								
*Cherax ?plebejus**	X	X	X	X	X	X	X	X

Appendix 1—continued

Taxon	Site							
	1	2	3	4	5	6	8	9
Insecta								
Collembola								
Sminthurides ?stagnalis	X	X	X	X	X	X	X	X
Xenylla sp		X			X	X		X
Brachystomella sp	X			X			X	
Isotoma sp		X			X	X	X	
Odonata								
Lestidae sp		X						
Ephemeroptera								
*Bibulmena kadjina**	X			X				X
*Nyungara bunni**	X			X				X
Plecoptera								
*Newmanoperla exigua**	X	X						
*Leptoperla australica**				X			X	
Trichoptera								
Leptoceridae								
*Lectrides parilis**						X		
Triplectides sp B*					X			X
Oecetis sp*				X		X		
Notalina sp*								X
Notalina sp A*								X
Symphytoneuria sp 1								X
Symphytoneuria sp 2	X	X				X		
Leptocerid sp 1				X				
Hydroptilidae								
*Acroptila ?globosa**						X		
Oxyethira sp*	X				X		X	
Hellyethira/Acritoptila sp	X		X		X	X	X	X
Hellyethira sp B*			X			X		X
Maydenoptila sp A*					X			
Maydenoptila sp							X	
Ecnomidae								
*Ecnomina ?trulla**				X				
*Ecnomus pansus**						X		
Ecnomidae sp				X				
Philoreithridae								
Kosrheithrus sp				X				
Hemiptera								
Diaprepocoris sp		X	X				X	
Notonecta sp		X	X					
Coleoptera								
*Sternopriscus browni**	X	X	X	X	X	X	X	X
*S. marginatus**				X				
S. sp 1		X	X					X
*Homeodytes scutellaris**		X	X					
*Rhantus suturalis**			X		X			
*Uvarus pictus**		X			X			
Antiporus sp*		X						
Helodidae sp*		X						
Hydrophilidae sp 1*		X						
Hydrophilidae sp 2						X		
Curculionidae sp 1			X				X	
Curculionidae sp 2							X	
Diptera								
Simuliidae								
*Austrosimulium funosum**	X			X	X			X
Austrosimulium sp A.x*	X			X	X			X
?Cnephia sp 1*				X	X			
?Cnephia sp 2*				X	X			
Ceratopogonidae								

Appendix 1—continued

Taxon	Site							
	1	2	3	4	5	6	8	9
sp A*				X		X		X
sp F				X		X	X	X
sp G		X	X	X		X		X
Tipulidae								
Limnophila sp				X				
Muscidae								
Limnophora sp	X			X				
Culicidae								
Anopheles sp		X	X		X	X		
Aedes sp	X	X	X					
Empididae				X				
Dolicopodinae				X				
?Sciomyzidae				X				
Chironomidae								
Tanypodinae								
*Paramerina levidensis**	X	X		X			X	X
Paramerina sp (*cf levidensis*)[SW6]	X	X		X		X	X	X
Macropelopia dalyupensis						X		
Ablabesmyia sp [SW25]		X				X	X	
Procladius sp [SW12]	X	X	X	X	X	X		
Aphroteniinae								
*Aphroteniella filicornis**				X				
Aphroteniella sp [SW21,?V30]*	X							
Orthocladiinae								
*Stictocladius uniserialis**	X			X	X			X
Stictocladius sp [SW32]				X				
*Crictotopus annuliventrus**				X				
Thienemaniella sp [V19]				X				X
Limnophes sp	X			X	X	X	X	
Parakiefferiella sp [V5C9]*	X		X	X	X		X	X
Orthocladiinae sp 1 (*cf Limnophes*) [SW7]	X						X	X
sp 2 (*cf Limnophes*) [V31]*				X		X		
sp 3 [SW23]					X			
sp 4 [SW28]				X				
sp 5 [SW29]				X				
sp 6 [SW30]				X				
sp 7 [VCD2]	X				X		X	X
Chironominae								
*Cryptochironomus griseodorsum**	X	X		X			X	X
*Chironomus aff. alternans**		X						
*Dicrotendipes conjunctus**		X	X		X			
Dicrotendipes sp [V47]	X	X	X			X	X	X
*Cladopelma curtivalva**	X		X	X		X	X	
Cladopelma sp [SW26]							X	
Kiefferulus martini							X	
Polypedilum sp A [V3]*				X		X	X	X
Polypedilum sp B [V33]*	X		X	X	X			
Riethia sp 1 [V4]*				X				X
Riethia sp 2 [V5]*								X
Harnischia sp [VCD10]*				X				
Paratendipes sp [V12]*						X		
Tanytarsus sp 1 [SW2]*	X	X	X	X	X	X	X	X
Tanytarsus sp 2 [SW3]*	X		X	X	X		X	X
Rheotanytarsus sp 1 [SW10]*			X	X				X
Rheotanytarsus sp 2 [SW20]	X			X	X	X		X
Stempellina sp [V7]*	X	X						

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Bioerosion, notch formation and micromorphology in the intertidal and supratidal zones of a calcareous sandstone stack

M Abensperg-Traun[1], G A Wheaton[2] & I G Eliot[1]

[1]Department of Geography, The University of Western Australia,
Nedlands, WA 6009

[2]Department of Agriculture, Division of Resource Management, Baron-Hay Court, South Perth, WA 6151

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Abstract

Variation in the magnitude of notch formation, and annual rates of bioerosion caused by *Littorina unifaciata* (Mollusca: Gastropoda) and *Clavarizona hirtosa* (Mollusca: Amphineura) with aspect and exposure, were assessed for the intertidal and supratidal zones of Shag Rock, a calcareous sandstone stack on the Western Australian coast near Fremantle. At eight profile stations around Shag Rock the gross morphology of the stack walls was surveyed and referenced to Australian Height Datum (AHD); the density of molluscs was established within discrete tidal and supratidal zones, and specimens taken for analysis of their gut contents. Molluscs accounted for approximately 1.1 cm^3 (Gastropoda) and 4.9 cm^3 (Amphineura) of inorganic material/yr per individual respectively. The highest rate of horizontal erosion was 0.8 mm/yr. This estimate is comparable with other estimates from Australia.

The visor and notch morphology varied systematically with aspect and exposure, with the notch being deepest, 2.0 to 2.3 m, on the exposed south and southwesterly profiles. The point of maximum notch formation corresponded with the highest density of molluscs on the rock face. It would have taken between 2 000 and 8 000 yrs of continued bioerosion at present rates of erosion for the notches to have formed. On six of the profiles, the morphology was further examined by measurement of surface roughness in 40 cm bands down the rockface. The highest roughness was recorded in the upper intertidal and supratidal zones, between AHD Zero and 0.8 m. This is consistent with the highest densities of *Clavarizona hirtosa*. Roughness decreased above and below this band. It increased again near the visor rim on the southerly and westerly profiles, where the upper part of the rockface is exposed to spray.

Introduction

Rates of erosion caused by two species of intertidal marine molluscs, *Clavarizona hirtosa* (Mollusca: Amphineura) and *Littorina unifaciata* (Mollusca: Gastropoda), were determined for intertidal and adjacent zones having markedly different aspect and exposure on a calcareous sandstone stack, Shag Rock, off Trigg Beach in Western Australia (Fig. 1). The objective of this pilot survey was to relate current rates of bioerosion to the morphology of the stack, particularly to configuration of the notch, as it varied with aspect and exposure.

It is well known that some marine molluscs cause direct erosion of the rock surface, as has been reviewed by Trenhaile (1980, 1987) and Spencer (1988). For example, North (1954) examined two Californian species of intertidal snail (*Littorina planaxis* and *Littorina scutulata*) (Mollusca: Gastropoda). He found that a 0.8 cm snail contained an average 1.6 mg of sand in the gut, and that the snails renewed their gut content 4-8 times daily. With a rock density of 2.2 g/cm^3, 100 snails of that size had the potential to excavate a basin of 86 cm^3/yr. Pioneering work was reported by Hodgkin (1964) from Point Peron, *ca* 45 km south of Trigg, Western Australia, and Norfolk Island in the southwest Pacific Ocean. He demonstrated that bioerosion was sufficient to have cut deep notches but not form shoreline platforms during the mid- to late Holocene. More recently, Hodgkin (1970) has described erosion caused by species of *Littorina* commonly known as periwinkles, as well as radula feeding marks characteristic of chitons (Mollusca: Amphineura). He found grazing marks as high as 70 cm above MHWS tide levels. Subsequent studies have supported Hodgkin's (1964, 1970) initial observations. Further reference to limestone erosion by molluscs was made by McLean (1974) for Barbados. Values of erosion for *Littorina* spp. of 0.15 and 0.4 cm^3/yr were established, while chitons gave values of 8.0 and 13.0 cm^3/yr. The combined amount of erosion by algal feeding gastropods and chitons suggested surface erosion and notch retreat in the intertidal zone of at least 2 mm/yr, which is approximately double the rate of erosion determined by Hodgkin (1964) from Western Australia and Norfolk Island. Trudgill (1983) has reported estimates of bioerosion, caused by grazing chitons, of between 0.2 and 0.7mm/yr. The rate of erosion associated with homesite excavation by chitons is an order of

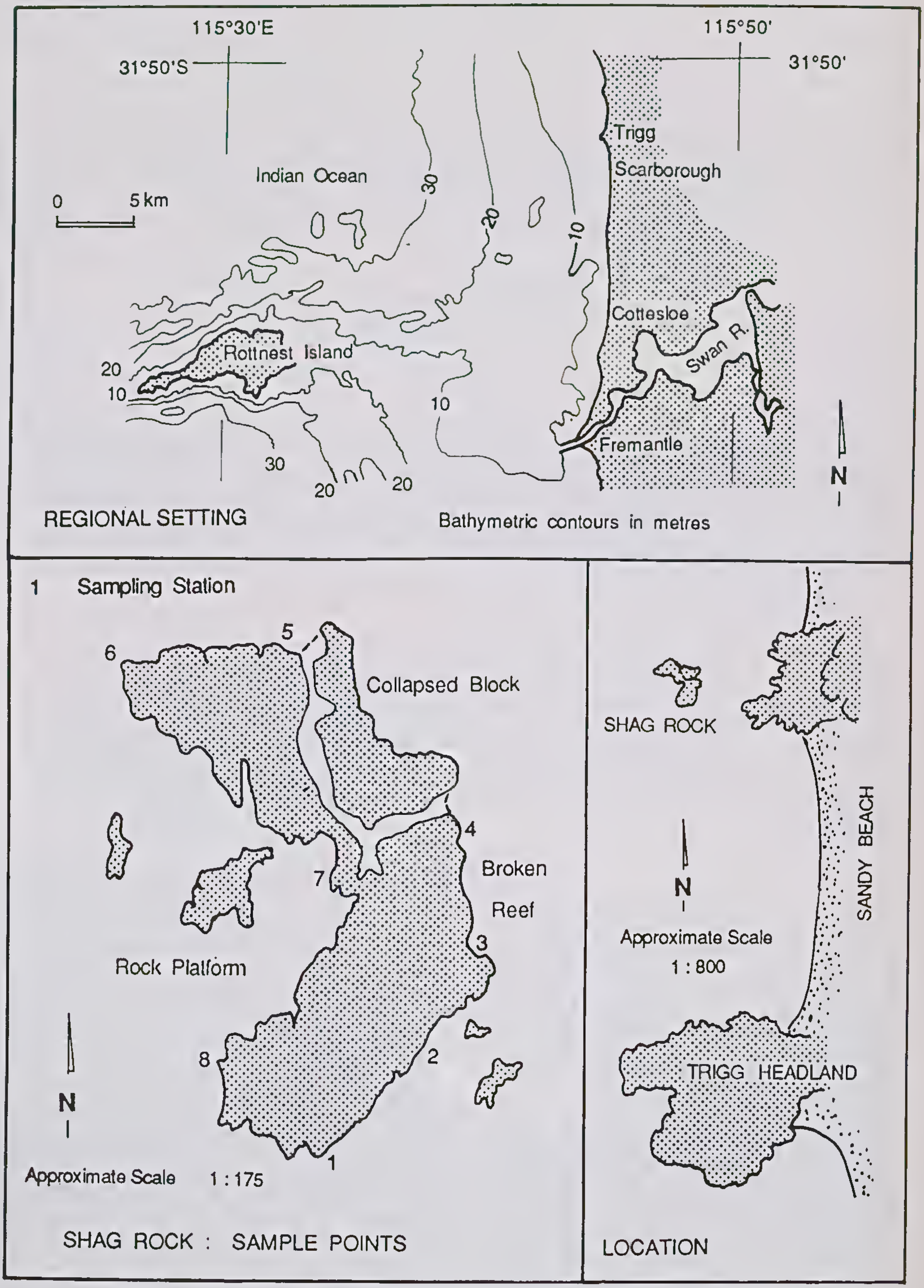


Figure 1 Regional setting and survey stations on Shag Rock at Trigg, Western Australia.

magnitude higher. McLean (1974) found that a typical homesite depression of a chiton (mean volume 55 cm^3) took less than 5 yrs to establish, and Trudgill (1983) reports chiton homesite excavation rates of 0.2 to 2.9mm/yr.

Intertidal marine organisms are very sensitive to desiccation. This results in zonal distributions, depending on degree of sensitivity (Hodgkin 1970, Lewis 1972). The abundance of animals and the rate of erosion will therefore vary with the duration and frequency of submergence. These factors are controlled by the tide and other sea level fluctuations, as well as the result of wave splash and spray, insolation characteristics, temperature fluctuations and nearshore variation in water chemistry (Stephenson & Stephenson 1949, Lewis 1972). Biological factors, including competition for food and space, trophic relations and predation (Paine 1980, Spencer 1988), also contribute to the zonation of marine organisms so that the distribution of bioerosion is probably not a simple relationship between the distribution of organisms and the physical parameters of the environment. Nevertheless, Evans (1968), working on the North American coast, found that rates of erosion within the intertidal zone increased with increasing exposure to sea water, and Hodgkin (1970) considered the rate of bioerosion fast enough to have cut notches up to 4 m deep during the Holocene. His proposition that bioerosion may account for a substantial proportion of notch development in limestone lithology is further examined here.

Study area

The limestone of the coast near Trigg is a coarse to medium grained calcarenite, composed of quartz sands and skeletal fragments, typical of the Tamala Limestone geologic unit described by Playford *et al* (1976). It includes Pleistocene marine and eolian sediments cemented in situ, chiefly by calcium carbonate, at a time when sea levels were lower than at present. The coastal limestones of the Perth Region are highly variable in calcium carbonate content, and hence in their hardness and strength, even within a small area (Tjhin 1981). They consist of both sandy calcarenite and calcareous sandstone, though at Shag Rock the latter predominates. Where it outcrops at the coast, the calcarenite has undergone several phases of marine erosion which has resulted in a distinctive assemblage of rock platforms, stacks, marine benches, beach ramps and low bluffs (Fairbridge 1950). The existing stacks and bluffs are now subjected to erosion by biological, chemical and mechanical agencies. This has resulted in the development of visors and intertidal notches similar to those described by Fairbridge (1950), Hodgkin (1964, 1970), Trudgill (1976) and Trenhaile (1980).

Shag Rock

Shag Rock is a small, calcareous sandstone stack on the northern perimeter of a 50 m wide rock platform. The stack rises to a maximum height of 2.1 m above MSL. Its upper surface slopes gently to the northeast. The stack is roughly V-shaped in plan form, with the V oriented towards the east (Fig. 1). There is considerable variation in the gross morphology of the walls of the stack with aspect and exposure. The visor and intertidal notch are best developed on the exposed northwest and southerly faces, particularly the latter. The notch varies from ca 0.6 m in depth inside the "V" to 2.5 m on the exposed southwesterly face. There is moderate visor development on the northern side of the stack, where the notch is ca 1.6 m deep. The leeward, easterly face is nearly vertical in some places and there are collapsed blocks in the channel between Shag Rock and the shoreline.

The biota of limestone platforms in southwestern Australia has been described by Hodgkin *et al* (1959), Marsh & Hodgkin (1962) and Black *et al* (1979). The dominant species at Shag Rock are *Clavarizona hirtosa* and *Littorina unifaciata*. Hence, they are the organisms examined. The molluscs apparently graze on an endolithic layer of cyanobacteria (*Oscillatoria* spp.) which covers the rock surface in the intertidal zone. Macro green algae (*Ulva lattuca*) are attached to the rock surface in some places.

Tides

Trigg is a microtidal environment (Davies 1980) where the coast experiences a mixed but predominantly diurnal tidal regime with a lowest to highest astronomic tidal range of 0.9 m (Anon 1988). Semidiurnal constituents are most apparent in the neap-tide phase when tidal ranges may be less than 0.1 m, whereas diurnal constituents dominate the spring-tide phase when the MLLW to MHHW range is approximately 0.4 m. The small tides of the region are frequently over-ridden by barometric pressure effects on sea level and by storm surge. The extra-tidal processes may at least double the range of sea-level variation due to the astronomical tides. Steedman (1977) reported that the extreme range of sea level recorded at Fremantle between 1896 and 1968 was 2.04 m, ranging from a low of 0.15 m below chart datum (recorded on 13 January 1896) to a high of 1.89 m (recorded on 10 May 1910). The passage of low-pressure systems may also generate long wave activity on the continental shelf (Allison *et al* 1980). These waves have periods up to 30 mins and amplitudes reaching 10 cm. The sea-level fluctuations combine to produce marked seasonal and lower frequency variation in submergence of the rock faces at Shag Rock.

In the context of this paper the term 'intertidal zone' refers to the area of rockface between MLLW and MHHW (Fig. 2) as the tidal levels are defined in the Australian National Tide Tables (Anon 1988). Upper and lower components of this zone are recognised in relation to MSL (AHD Zero) and the 'supratidal zone' is loosely taken to represent the zones of highest astronomical tide ranging, surge inundation and wave splash. Under storm wave action, wave splash occurs to the roof of the notch, at least, and spray covers the crest of the stack. The definition of the supratidal zone used here is consistent with the term 'supralittoral fringe' used by Lewis (1964). In both instances the upper limit of the zone is set by the upper limit of *Littorina* spp.

Waves

In the vicinity of Trigg, the Western Australian coast is dominated by a low- to moderate-energy deep-water wave regime characterised by a persistent south to southwest swell (Silvester 1976). Waves measured in deep

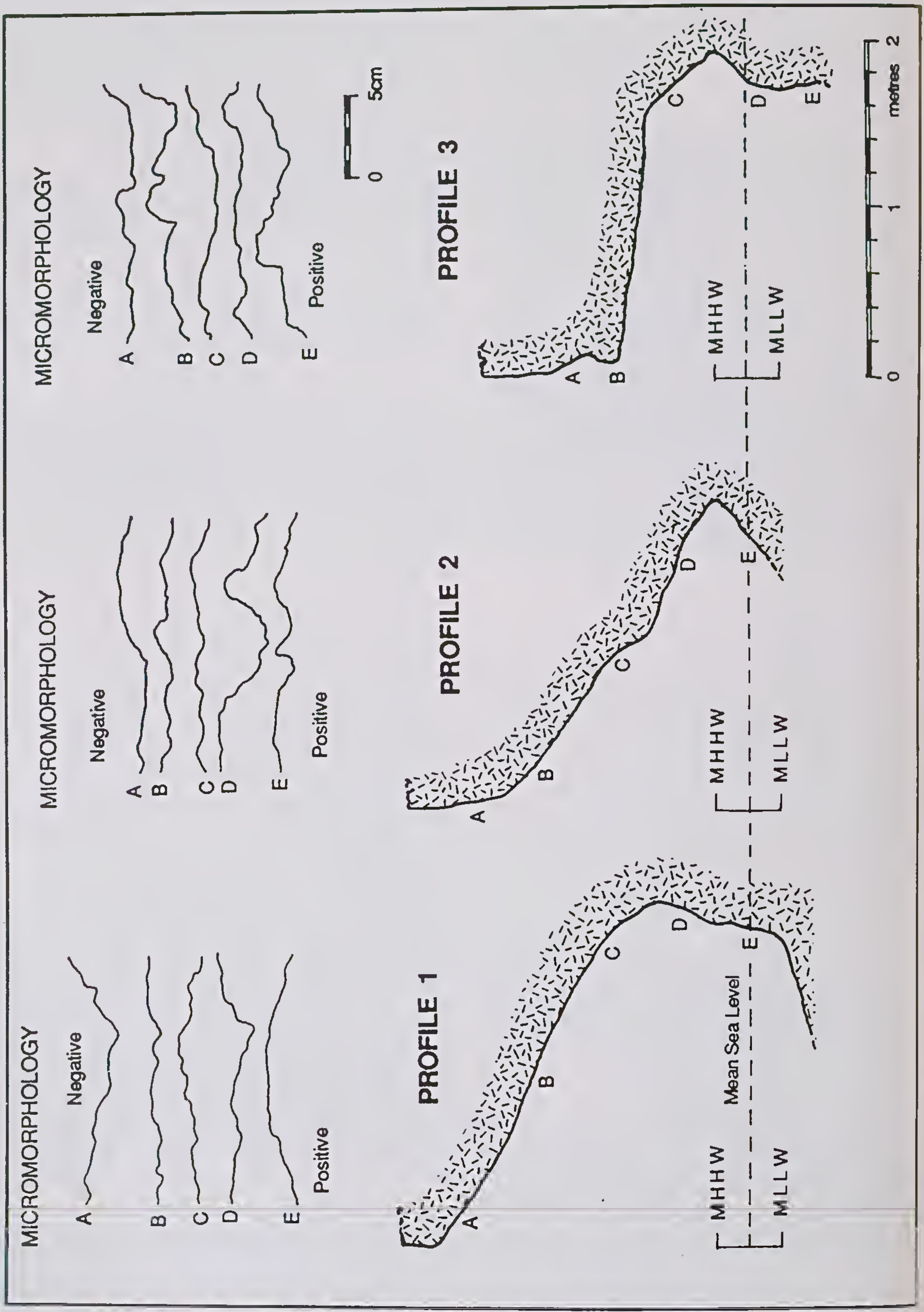
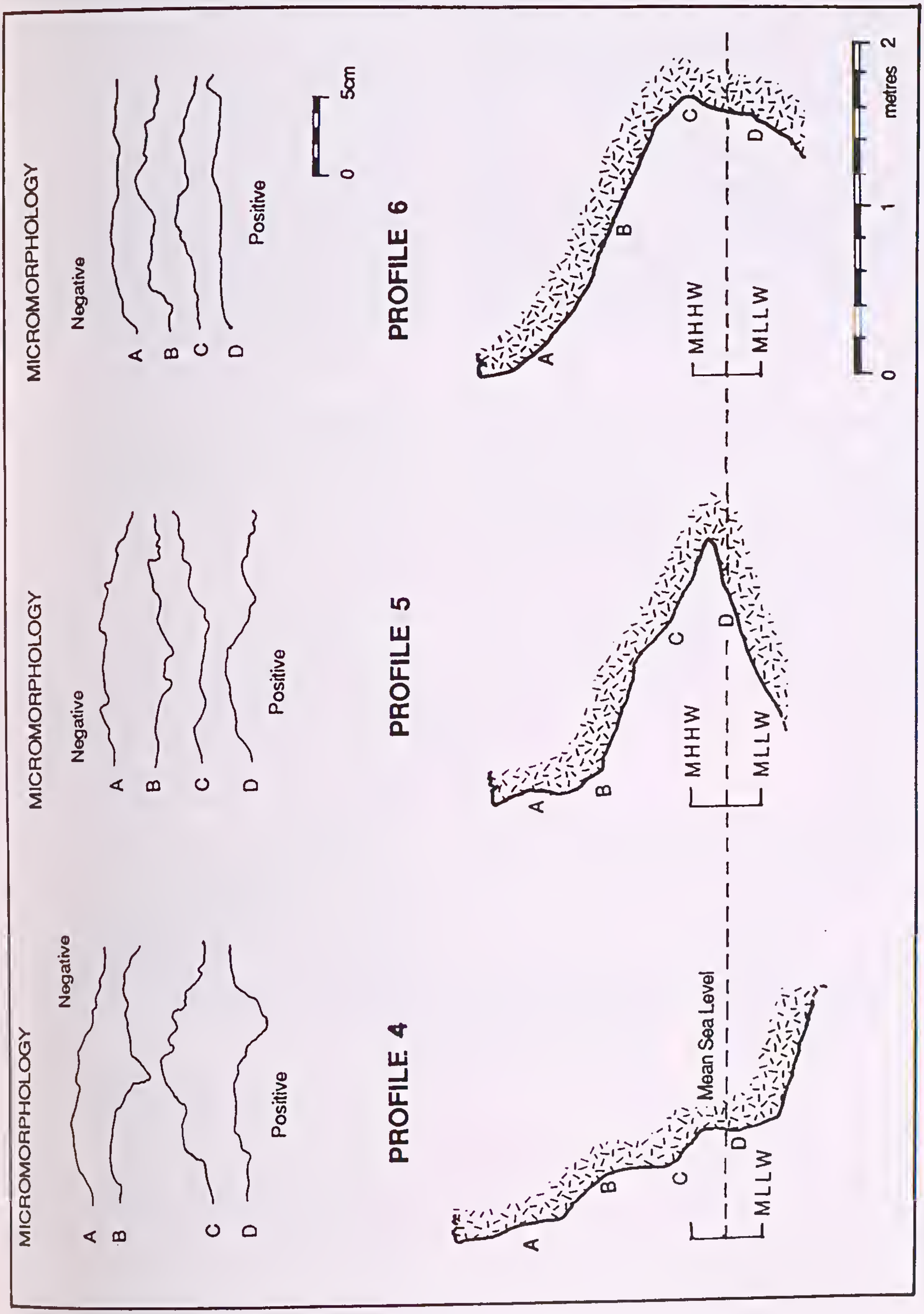


Figure 2 Profiles of rock faces at Shag Rock. The profiles show the diversity of visor and notch formation around the stack as well as micromorphologic variation within each profile. The positive face is exposed to the atmosphere.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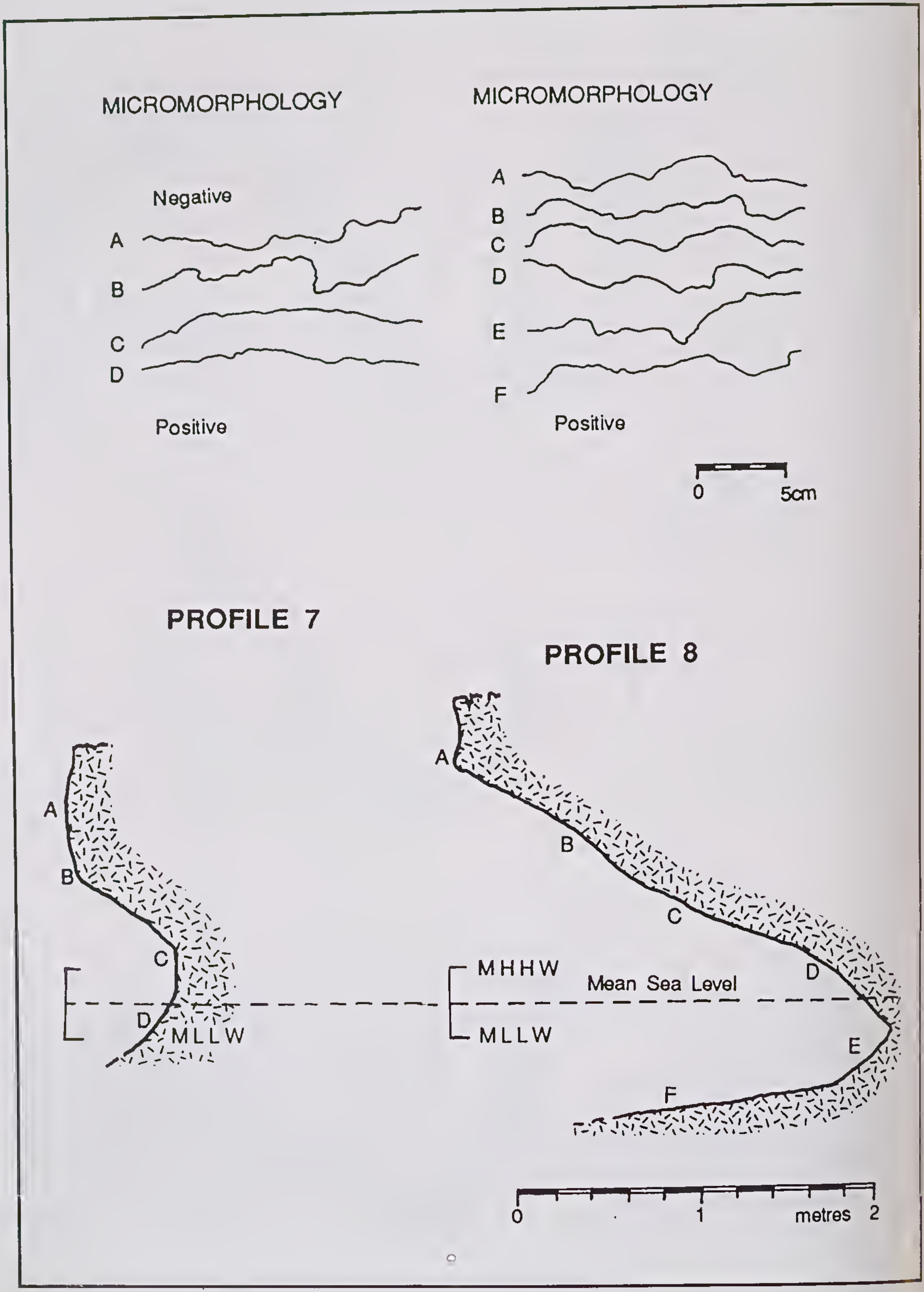
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water off Garden Island (Steedman 1977, Riedel & Trajer 1978) and inside the reefs at 10 m depth off Mullaloo Point had median significant heights of 1.4 and 0.4 m, respectively, modal maximum heights of 2.0 - 2.5 and 1.0 - 1.5 m, respectively, and modal periods of 6 - 7 secs in both instances. Wave conditions at Trigg fall within these bounds. There is little variation in the low wave energy from year to year for the period December through May (summer to autumn). However, the wave climate is more severe between May and November (winter to spring), with large variations possible between successive years. At Trigg, waves break over the seaward margin of the rock platform under all but very low tide and wave (H_{max} < 0.5 m) conditions and Shag Rock is generally hit by surf bores travelling across the shoreline platform rather than by breaking waves. Hence, mechanical wave erosion would be less than might occur under shock pressures generated by waves breaking against the stack.

Materials and methods

The study was carried out over a three-week period during July and August 1985. Profiles of the rockface (Fig. 2) were obtained by measuring the vertical and horizontal components from a plumb line at eight positions around the upper rim (visor) of the rock (Fig. 1). The profiles were later tied to a fixed benchmark and related to Australian Height Datum (AHD) by means of a closed survey traverse.

The grazing action and homesite excavation of biolithofagic organisms potentially leads to variation in the micromorphology of the rock surface. For example, chitons and sea urchins excavate different shaped homesites (McLean 1974, Trenhaile 1987). The micromorphology of the rock face on each profile (Fig. 2) was surveyed by using a Temco Template Former. The surface irregularity was expressed in terms of a Roughness Coefficient (RC) following Barton & Choubey (1977). Each coefficient was calculated as the standard deviation of surface elevation measured at 2 mm intervals along 15 cm long profile segments in 40cm bands down the rockface. The elevations were detrended prior to calculation of the variance.

In conjunction with the micromorphological surveys, a Schmidt Hammer (Barton & Choubey 1977) was used to establish the shear strength of the rock surface at three profile stations. It was considered that measurement of shear strength could provide an indication of the susceptibility of the rock surface to bioerosion. Barton & Choubey (1977) recommended that 10 readings per surface area be taken, the lowest five discarded and the mean of the highest five accepted as an indication of shear strength. Their recommendations were followed for the survey on Shag Rock.

Within each face, vertical zones were identified on the basis of the distribution, abundance and species of mollusc present as well as by the morphology. In turn, these were related to AHD. The upper zone was an area which extended ca 50 cm downwards from the visor and coincided with low densities of *Littorina unifaciata*, the only species present; the middle zone was located in the central area of the overhang and contained higher densities of *Littorina unifaciata* only; the lowest zone coincided with the notch. It lacked *Littorina unifaciata* but was inhabited by *Clavarizona hirtosa*. The lowest zone was extended to well below MSL in some instances. Molluscs were collected from 20 x 20 cm quadrats which were placed randomly within each zone on each of four profiles. Three quadrat samples were made in each instance, yielding a total of thirty-six, 20cm^2 samples. The insoluble content of the mollusc digestive tracts (largely quartz sand particles) were determined by following the procedures described by McLean (1974) and Ayre *et al.* (1977).

An estimate of bioerosion in the upper and lower intertidal and supratidal zones was calculated in three steps. The average, insoluble gut content was multiplied by four to obtain the daily, and hence annual, rates of ingestion, following North (1954). This was then converted to a volumetric erosion rate by considering mollusc densities for 20cm^2 quadrat samples. Rates of surface erosion in mm/yr were then estimated on the basis that 2.2g of rock equals 1cm^3 in volume.

Results

Macromorphology

The upper surface of the stack has a northeasterly slope so that the crest of the visor is highest (2.1 m) in the southwest and lowest (1.3 m) to the northeast. The overhang varies in shape with aspect and exposure to wave and current activity (Fig. 2). The notch is deepest (2.0 - 2.3 m) on the south and southwest profiles and least on the western wall, inside the 'V'where it is 0.65 m deep. The deepest part of the notch is apparently related to exposure to the prevailing wind, surf bore, wave splash and current activity. In general, the elevation of the notch is close to the upper tidal zone. It lies between 0.1 m and 0.2 m above AHD Zero on most profiles. Exceptions to this occur on the southern profile, where the deepest point is 0.6 m above, and on the eastern profile where it is 0.5 m below, AHD Zero. The exceptions respectively correspond with the most exposed and protected aspects of the stack.

Micromorphology

The highest roughness coefficients were recorded in the upper intertidal and supratidal zone, between AHD Zero and 0.8 m (Table 1). Roughness decreases above and below this band. It increases again near the visor rim on

Table 1

Surface roughness coefficients. Each coefficient was calculated as the standard deviation of detrended surface elevations measured at 2mm intervals along a 15cm profile segment. E = Elevation of segment centre above Australian Height Datum (m). R = Roughness coefficient (mm); — = no data.

Distance below rim of visor (cm)	Aspect							
	Profile 1 (South)		Profile 3 (East)		Profile 6 (North)		Profile 8 (S-West)	
	E	R	E	R	E	R	E	R
40	1.6	5.3	1.2	5.7	1.0	3.1	1.3	10.8
80	1.2	3.3	0.8	6.0	0.6	6.5	0.9	5.1
120	0.8	15.3	0.4	3.5	0.2	13.1	0.5	13.4
160	0.4	4.9	–0.1	6.1	–0.2	3.2	0.1	5.5
200	0.0	6.0	–0.5	5.1	—	—	–0.3	7.2

the southerly and westerly profiles, where the upper part of the rockface is exposed to spray. High values were also recorded in the lower intertidal zone of profiles on the southern half of the stack. With the exception of the sheltered eastern profile, the zone of greatest roughness on each profile was coincident with the highest densities of *Littorina unifaciata* and the roughest profiles were those facing to the west and southwest.

Estimates of rock hardness determined by Schmidt Hammer, point-load testing at Shag Rock indicate a very low shear strength . The Schmidt Hammer values ranged from 1.0 to 3.3, without systematic distribution. The results are apparently due to the very low calcium carbonate content (27.8%) of the calcareous sandstone comprising the stack. They indicate the susceptibility of the rock to erosion but are too low to facilitate a valid analysis of differential rates of surface erosion and notch retreat.

Bioerosion

Littorina unifaciata and *Clavarizona hirtosa* showed distinct vertical stratification, and hence were used as a factor in identification of zones for sampling. The principal variation in density was related to aspect. The gastropods clearly preferred the middle zone of the easterly and southerly faces (Table 2) whereas aspect appeared not to affect chiton density.

Littorina unifaciata samples were found to contain a mean value of 1.3 mg of inorganic material per individual (mean length of snails 5 mm). Assuming an average turn-over of stomach contents of four times/day (North 1954), 1.9 g of surface rock would be removed every yr by each snail. This compares with 8.8 g/yr for *Clavarizona hirtosa* (mean length 33 mm), assuming the same daily rates of stomach turn-over. Chiton specimens contained a mean of 6.0 mg of inorganic material per individual (Table 2).

The calculated rates of erosion (g/yr) were then used to assess rates of notch retreat (mm/yr). Erosion rates in the upper intertidal zone ranged from 0.2 mm/yr on the northern profile, to 0.8 mm/yr on the southern profile (Table 2). Erosion rates were generally highest in the south-eastern part of the stack. In the lower intertidal zone, erosion rates were less variable, ranging from 0.4 mm/yr on the east profile, to 0.5 mm/yr to the west. Assuming that bioerosion commenced on a near vertical surface, and that the current rate of bioerosion has been constant, an estimate was made of the time required to account for the notch formation observed at each face on the stack. The amount of time required for maximum notch formation at the estimated rate of erosion varied from ca 2 000 yrs for the east face (Profile 3), to 8 000 yrs for the north face (Profile 7). The estimates are indicated in Table 2.

Discussion

Although assumptions underlying the formation of notches at Shag Rock are somewhat sweeping, the estimated rates of surface erosion and notch retreat are consistent with rates of bioerosion reported elsewhere. A mean of 1.1 cm^3/yr for *Littorina unifaciata* at Trigg compares with 0.8 cm^3/yr reported for a Californian species of *Littorina* (North 1954). Similarly, a value of 4.9 cm^3/yr for *Clavarizona hirtosa* at Trigg compares with 8 cm^3/yr suggested for a species of chiton by McLean (1974). Homesite excavation of *Clavarizona hirtosa*, reportedly accounting for ca. 10 cm^3/yr per individual chiton (McLean 1974), was not taken into account although variation in micromorphology indicates that this might be significant. The estimated range of surface erosion and notch retreat of 0.2 mm to 0.8 mm (Table 2) compares very closely with rates of 0.2 mm to 0.7 mm reported by Trudgill (1983) for an intertidal limestone feature on the Great Barrier Reef. The rate of erosion by non-biotic

Table 2

Mollusc densities and distribution; annual rates of bioerosion (g/yr); annual rates of surface erosion and notch retreat (mm/yr); and the estimated time for the notch to have been cut by bioerosion (yrs) for supratidal, upper and lower intertidal levels on the rock face. The intertidal zones are defined with respect to Australian Height Datum (Fig. 2)

Aspect	Tidal zone	Mollusc no.^{s}/20cm^2		Annual erosion (g)		Annual erosion rate (mm)	Depth of notch (m)	Time for notch to form (years)
		Amphineura	Gastropoda	Amphineura	Gastropoda			
Profile 1 (South)	Supra	0.0	7.0	0.0	13.5	0.15	0.0	0.0
	Upper	0.0	35.3	0.0	68.1	0.76	1.6	2 000
	Lower	4.3	0.0	37.7	0.0	0.42	1.9	4 750
Profile 3 (East)	Supra	0.0	13.3	0.0	25.7	0.28	0.0	0.0
	Upper	0.0	29.3	0.0	56.4	0.63	1.7	2 833
	Lower	4.0	0.0	35.1	0.0	0.39	1.7	4 250
Profile 6 (North)	Supra	0.0	0.0	0.0	0.0	0.00	0.0	0.0
	Upper	0.0	7.3	0.0	14.1	0.15	1.6	8 000
	Lower	4.6	0.0	40.4	0.0	0.45	1.5	3 000
Profile 7 (West)	Supra	0.0	0.0	0.0	0.0	0.00	0.0	0.0
	Upper	0.0	7.6	0.0	14.7	0.16	0.8	4 000
	Lower	5.0	0.0	43.9	0.0	0.49	2.6	5 200

processes, such as those reviewed by Trenhaile (1987) and Spencer (1988), are arguably greater in areas where surface roughness is greatest and exposes a larger surface area to mechanical and chemical processes (McLean 1974).

It is questionable whether the rate of bioerosion can be used to explain the depth of the notch for different levels on the rockface, assuming that the calculated erosion rates have been consistent in the past and that erosion commenced on a near-vertical face. The wide range of estimates of surface erosion from different faces on the stack indicates that other factors may contribute to notch retreat. Notch formation is also facilitated by physical and chemical agencies (Trenhaile 1987) which were not considered in this survey. Also, less obvious effects of bioerosion have been pointed out by McLean (1974). These include an increase in the surface area of rock exposed to mechanical and chemical weathering as well as reduction of the resistance of the rock surface to mechanical processes. On Shag Rock, the surface roughness varied systematically with location with respect to tidal level and with the distribution of the biota. The roughness was greatest in the lower intertidal zone (Fig. 2). It decreased towards the visor. Shear resistances, recorded as Schmidt Hammer impacts, were highest in the supratidal zones.

The findings of this study are generally consistent with Hodgkin's (1964, 1970) time estimate for Holocene notch formation. His contention was that bioerosion was fast enough to have cut notches up to 4 m deep during the Holocene but was not of sufficient magnitude to explain the formation of shoreline platforms. This was also the case at Shag Rock. If present-day sea levels and current rates of bioerosion were stable over the last 6 000 yrs, all the other erosive agents would account for less than half the material eroded from the stack during that period, given the somewhat unreasonable assumption of near vertical faces on the stack. Profile determinations of the south and west faces, where the undercut was measured to sufficient depth, show that bioerosion is greatly reduced below the low water mark (Fig. 2).

The extent of wave-induced erosion may not be immediately apparent. While, for instance, erosion is consistently more extensive near the notch and less marked near the visor, the suggested rates of bioerosion could account for that. Evans (1968) commented on the highest point of the notch usually being level with the high water mark. There is considerable diversity in location of the notch with respect to mean sea level (AHD zero) at Shag Rock (Fig. 2). The maximum horizontal extent of the notch occurs approximately at MLLW level on Profile 8. It is within the intertidal zone on Profiles 4 and 5; at MHHW on Profiles 2, 3 and 6; and above MHHW elsewhere. This variation may reflect reduced mollusc densities (Table 2) rather than reduced wave energy, although the notch tends to be lowest on the leeward side of the stack. A maximum rate of notch retreat of 0.6 mm/yr for the sheltered east face compares with 0.8 mm/yr for the exposed south face. Nevertheless, the north face can be expected to be the most protected under the prevailing south-westerly wave regime and its relatively low rate of surface erosion of 0.5 mm/yr may reflect this. Considering exposure to wave energy as an indication of the source of maximum physical erosion, the exposed south and west faces should be expected to show deeper notches than the relatively sheltered north and east faces, as is the case at Shag Rock.

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Distribution, habitat and behavioural patterns of *Nickerlea sloanei* (Lea) (Coleoptera : Cicindelinae) in Southwestern Australia

Graham P Hall & Gordon R Friend

Department of Conservation & Land Management, Wildlife Research Centre, PO Box 51, Wanneroo WA 6065

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Abstract

Until now only seven specimens of *Nickerlea sloanei* (Lea) have been collected and the species has been considered rare. The acquisition of a large series of fresh material allows data to be presented on the spatial and temporal distribution of the species. A quantitative description of the habitat and notes on the activity and behaviour of individuals in the field are given. The species inhabits *Acacia* and *Allocasuarina* dominated shrublands and species-rich heath shrublands between the 250 and 350 mm isohyets of the inland south-west of Western Australia. Adults are active for only a very short period between late February and late March, in association with significant rainfall events. Nothing is known of the immature stages of the life cycle.

Introduction

The genus *Nickerlea* Horn contains two species; *distypsideroides* Horn from northern Australia, and *sloanei* (Lea) from southwestern Australia (Sumlin 1985). Only the holotype of the former species is known and until now, only seven specimens of the latter have been collected.*

However the acquisition of freshly collected *N. sloanei* from pitfall traps allows a reappraisal of the species spatial and temporal distribution, as well as a quantitative analysis of its habitat. Observations of individuals in the field also provide some data on the species' activity and behavioural patterns.

Methods

Most specimens were collected in pitfall traps ("Solo" plastic cups, 85mm diameter x 110mm deep), each containing a small amount of Galt's solution (70% sodium chloride, 15% potassium nitrate, 15% chloral hydrate and a few drops of glycerine). Traps were arranged in 15 x 15m grids, each with 16 traps spaced 5m apart, and were operated for 10 days every second month from November 1987. Prior to this date some preliminary trapping using smaller pits (plastic specimen tubes, 40mm diameter x 105mm deep) was undertaken, commencing mid 1986.

Distribution

Spatial

Western Australia: Mullewa (type); Cue ?(Horn 1926); 15 km NW Badja, 28°31'S, 116°40'E, 17-18 iii 1982, T F Houston & B Hanish (3M, 1F); Durokoppin Nature Reserve 31°18'S, 117°50'E, 35 km NNE Kellerberrin, 1-10 iii 1988 G Friend & D Mitchell (16M, 12F), 21-25 iii 1988 G T Smith & G P Hall (1M), 26 ii 1989 to 8 iii 1989 G Friend & D Mitchell (22M, 61F), 16-26 iii 1989 G Friend & D Mitchell (8M, 7F); 20 km NW Kellerberrin, 16 iii 1988, G T Smith and C Dickman (1F); East Yorkrakine Nature Reserve 31°24'S, 117°39'E, 30 km NE Tammin, 16—26 iii 1989 G Friend and D Mitchell (2M, 3F); Heitman's Scrub 31°31'S, 117°34'E 20 km NE Tammin, 16-26 iii 1989 G Friend and D Mitchell (1M). These sites are shown on Fig. 1.

The specimens collected near Kellerberrin and Tammin in 1988 and 1989 represent a southerly extension to the known distribution of *N. sloanei* by over 300 km. Representative specimens have been deposited in the Western Australian Museum, Perth, and the Australian National Insect Collection, Canberra.

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* A series of specimens of a new *Nickerlea* species was collected in mallee-heath shrubland in the Stirling Range National Park (34°28'S, 118°15'E, 320 km south of Kellerberrin) in February 1990.

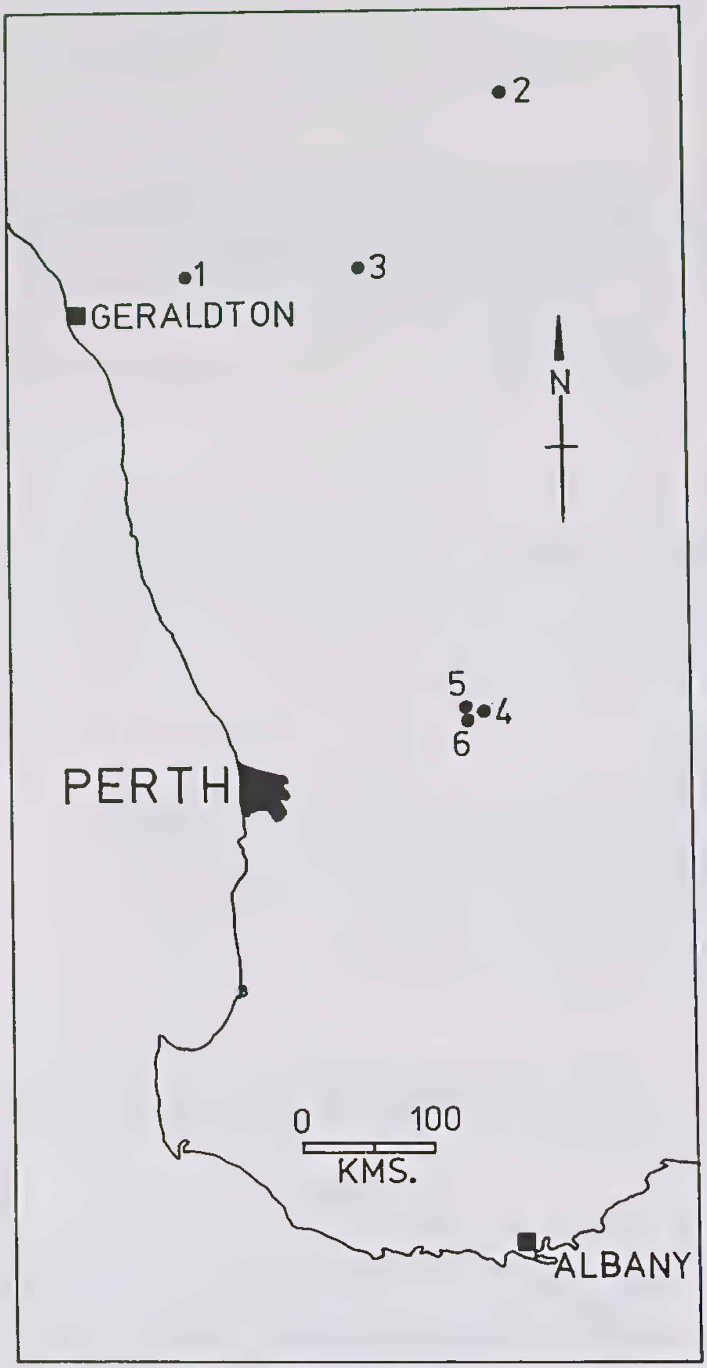

Figure 1 Collection sites (•) of *Nickerlea sloanei* in south-western Australia. *1* Mullewa, *2* Cue, *3* Badja, *4* Durokoppin Nature Reserve, *5* East Yorkrakine Nature Reserve, *6* Heitman's Scrub.

Temporal

Of the 140 specimens of *N. sloanei* recorded here, the time of collection is known for 138. It is noteworthy that all of these specimens have been collected between late February and late March. These data further define the temporal activity of Sumlin (1985) from "late summer/early fall" to a 4 week period between late February and late March. Furthermore, the limited data available suggest that activity periods may be associated with, or immediately precede the first significant rains of early autumn. The specimens collected by Houston & Hanish in 1982 followed a heavy fall of rain in that area (Sumlin 1985), while in 1988 very heavy drought-breaking rains fell near Kellerberrin during the week 21-25 March. No such rainfall events occurred in the 1987 season (which was characterized by severe drought) and, although regular trapping had commenced in mid 1986, no *N. sloanei* were collected in 1987. The 1989 data further suggest that adults may emerge immediately before or after significant late summer rain which is not the beginning of general autumn rain.

Habitat

Until now the habitat of *N. sloanei* has been the subject of speculation (Sloane 1906, Sumlin 1985). The Kellerberrin and Tammin series allows a data-based description of the habitat to be reported. By the classification of Walker & Hopkins (1984) vegetation at the Durokoppin collection sites comprises a mid-height sparse heath shrubland with isolated emergents to 4-5m high. About 90% of the foliage is below 1m with a mean projected foliage cover (<2m) of 45%. Canopy cover (>2m) varies between 0 to 15%. The ground surface is about 85% bare, with leaf litter, woody litter ("trash" >5mm diameter) and surface vegetation each accounting for 5%.

Soils on the pitfall trap grids at Durokoppin Nature Reserve comprise yellow-brown sands supporting a relatively rich flora. The most common plant species include the sedge *Ecdeiocolea monostachya*, and the shrubs *Astroloma serratifolium*, *Baeckea floribunda*, *Leucopogon hamulosus*, *Melaleuca conothamnoides* and an unnamed *Melaleuca* sp., *Verticordia chrysantha* and *V. picta*. Emergent taller shrubs comprise *Allocasuarina acutivalvis* and *Grevillea* spp. (*G. eriostachya*, *G. integrifolia* and *G. pritzelii*). In areas adjacent to the trap grids where the soil is more lateritic *Dryandra cirsioides* and *Mirbelia spinosa* occur, while *Eremaea pauciflora* and *Gompholobium* sp. are common in areas of white sand. Isolated individuals of *Xylomelum angustifolium* (woody pear) also occur throughout the habitat. The date of the last burn on Durokoppin is uncertain, but was probably in the 1920s.

The specimens from East Yorkrakine Nature Reserve were collected from grids in the far south-western corner of the reserve. The vegetation at this locality is described by Muir (1980). *Allocasuarina acutivalvis* and *Acacia stereophylla* are codominant and form a very tall (4-5m) mid-dense shrub stratum with c 65% canopy cover, and there is a sparse understorey of the sedge *Ecdeiocolea monostachya*. Soils are similar to those at the Durokoppin site. This reserve was last burnt by a high-intensity fire in summer 1927 (F L Diver, pers comm). The vegetation at the Heitman's Scrub site is very similar to that sampled on East Yorkrakine Reserve; this remnant is on private property and was last burnt before the turn of the century (Gardner 1957, B Y Main pers comm).

Activity and behaviour

Numerous adult *N. sloanei* were observed in the field on 26 ii 1989 during a pitfall trapping session between 26 ii 1989 and 8 iii 1989 at Durokoppin Nature Reserve. This followed significant summer rain (30.5mm) on 25 ii 1989.

Six live specimens were brought back to the laboratory in an attempt to establish a breeding colony, but this was unsuccessful.

In the field, animals were observed to run very rapidly then fly off, first vertically then horizontally, at high speed when approached. Consequently they are a very difficult species to observe and/or capture. Two of those captured alive were copulating. Specimens were observed between 1130 and 1500 h; weather conditions were fine and sunny, temperatures were between 26.0 to 32.0 C with about 50% relative humidity, and there was a strong easterly wind of about 25 km/h.

Discussion

The results reported here indicate that *N. sloanei* is probably restricted to widely separated areas between the 250 and 350 mm rainfall isohyets of the inland south-west of Western Australia. Within this region the species occupies habitat varying from *Acacia* shrubland (Sumlin 1985) to medium to tall species - rich heath shrublands on yellow-brown sands. A large proportion of this vegetation has been cleared in the past 60-80 years for agricultural and pastoral purposes. This has resulted in the formation of small, isolated patches of native vegetation with substantially altered grazing and fire regimes, which in turn may have caused significant changes in the quality of these patches as habitat for *N. sloanei*. We therefore suspect that the viability of some *N. sloanei* populations in the region is tenuous.

In addition to the fragmented condition of suitable habitat, the very narrow and deterministic nature of the species' activity patterns further complicates an assessment of its conservation status. The low number of specimens previously recorded may be a reflection of these features of the species life history. Clearly, *N. sloanei* is quite common after significant summer-autumn rainfall in the sandy heath shrubland habitats near Kellerberrin and Tammin, but more surveys are required following such rainfall events in other areas to accurately determine its status and distribution. Data from further collection sites need to include detailed habitat measurements to help determine the species' full habitat requirements.

Despite our information on adult *N. sloanei*, there is nothing known about the immature stages. The surface soil and litter at Durokoppin in late summer is very hot and dry, so we assume that females either deposit their eggs in a moist sub-soil chamber, or provide them with properties which reduce dessication until they hatch after the autumn rains.

The distribution and habitat of *N. distypsideroides* remain unknown. However, the information from *N. sloanei* may provide some clues as to when, if not where, to begin searching. If *N. distypsideroides* is present in Western Australia, then those northern areas of the State subject to summer cyclonic rainfall may be of interest, given the appearance of *N. sloanei* in hot weather associated with significant rainfall.

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Radiocarbon ages of some coastal landforms in the Peel-Harvey estuary, south-western Australia

V Semeniuk & C A Semeniuk

21 Glenmere Road Warwick WA 6024

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Abstract

The stratigraphy and ^{14}C chronology of a tidal shoal, a stranded channel shoal complex, a relict tidal delta, a stranded estuarine embayment, a beachridge system, and a lobate delta in the Peel-Harvey estuary of southwestern Australia show that these landforms began forming as early as c. 7000 yr BP, when the sea first flooded the estuary, while others are relatively young (< 1000 yr BP). Estuarine-marine conditions had established by about 8500 yr BP, and relative sealevel had reached 2.2 m above present by about 7000 yr BP in the northern estuary. The radiocarbon ages and sealevel indicators obtained from northern estuary settings appear to conform to a falling sealevel curve from about 4000 yr BP to the present. Data from coastal peats buried under some beachridges show that relative sealevel was 2 m and 1 m below present level some 7000 and 6400 yr BP, respectively, in the southern parts of the estuary. Shell dated at c. 6000 yr BP from mud filling an abandoned channel in the Murray—Serpentine River delta indicate that this lobate delta first formed prior to that time, implying a possible pre-Holocene origin for the delta complex.

Introduction

The coastal landforms of the Peel-Harvey estuarine system consist of variably disposed beachridges, marginal platforms, fluvial deltas, tidal deltas and shoals, spit-lagoon complexes, and equivalents of some of these units stranded during times of higher Holocene sealevels (Brown *et al.* 1980, Semeniuk & Semeniuk 1990). To date, however, there has been no description of these coastal landforms in terms of their chronology. Brown *et al.* (1980) and Brown (1983), for instance, report only three radiocarbon dates for the whole estuarine system, but do not relate these dates to past sealevels by using sealevel indicators, nor do they determine the chronology of any of the estuarine sequences. During recent stratigraphic investigations into the coastal landforms and peripheral wetlands of the Peel-Harvey estuary (Semeniuk & Semeniuk 1990), as part of the ongoing studies by the authors into freshwater and estuarine wetlands (C A Semeniuk 1988), various shelly, peaty, and wood-bearing horizons were sampled for the purposes of dating the coastal stratigraphy of this estuary. This paper reports the results of these chronological studies, including the dating of sealevel indicators in some sequences. It also compares the sealevel history in the estuary with other sealevel records in the region.

Methods

The stratigraphy of the estuarine landforms of the Peel-Harvey estuary was investigated by soil sampling, trenches, cores, augering, reverse-air-circulation coring to 30 m, and topographic levelling along transects intersecting the main coastal landforms (Figs 1 & 2; see also Semeniuk & Semeniuk 1990). The structure, fabric, texture and composition of soil and underlying stratigraphic samples were studied in the laboratory to define the lithologic suites. Within trenches and cores, samples were collected for radiocarbon analysis from *in situ* layers. The reverse-air-circulation corer extracted samples in 0.5 m to 1.0 m segments as desired, and could extract material from precisely determined depths. The core material will be housed in the core storage facilities of the Geological Survey of Western Australia.

Eight types of samples for radiocarbon dating were collected from the sequences. These were:

1. mainly monospecific shell wholly within the estuarine sediments, in order to date the containing sequence and hence the landform;
2. mixed shell wholly within the estuarine sediments, in order to date the containing sequence and hence the landform;

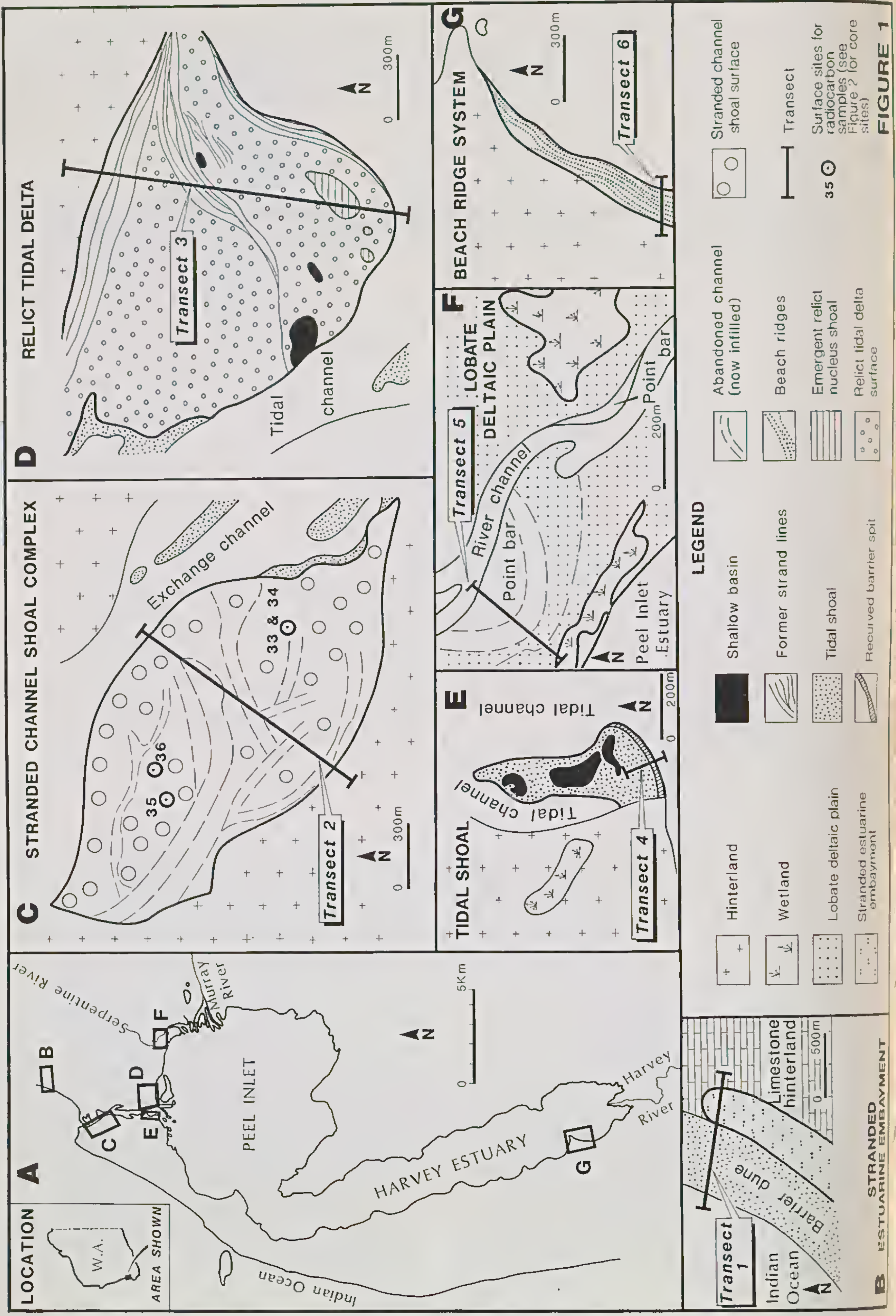

Figure 1 A Map showing study area and location of more detailed study sites; B-G Geomorphic maps of each of the study sites showing geomorphic components and location of stratigraphic transects and location of surface sample sites for radiocarbon material. Figure 2 shows location of subsurface sample sites for radiocarbon material.

3. mainly monospecific shell wholly within the estuarine sediments, but in association with a sealevel indicator, in order to date the sequence and the landform, and determine the position of past relative sealevel;

4. peat and peaty sand wholly within the shoreline estuarine sediments, in order to date the sequence and the landform, and determine the position of past relative sealevel;

5. wood imbedded in Pleistocene limestone to date the inundation by the Holocene transgression of the terrestrial surface;

6. mixed shell at the contact between the estuarine sediments and Pleistocene limestone in order to date the base of the estuarine sequence at the unconformity;

7. shell (chamiids and oysters) encrusting on pinnacles and islands of Pleistocene limestone protruding into the estuarine sediments in order to date the position of a former sealevel; and

8. shell wholly within the partially cemented Pleistocene limestone in order to confirm a pre-Holocene age for the limestone, thus ensuring that the sediments are not cemented Holocene materials.

Information on the samples used in radiocarbon analyses is presented in Table 1.

Shell, peat, and wood materials for radiocarbon analysis were thoroughly dried in a laboratory oven. Shells were washed, sorted into taxa, and clean, lustrous specimens of the abundant species, free of any adhering matrix, cementing agents, and discolouration, were selected. Where possible, only monospecific samples were used for analysis (Table 1). Where shells were abundant, enough material of two or more separate species could be sorted, thus providing replicate samples of different taxa for radiocarbon analysis at particular sampling sites and stratigraphic horizons. Where shells in samples were not abundant enough to extract sufficient of a single species, then clean, lustrous shells of various species were used in the analysis. Radiocarbon analyses were carried out by Kreuger Geochron Laboratories. In this paper radiocarbon dates are reported as "years BP", but we imply that these ages are in "^{14}C years BP".

While we accept in principle that there is some correction that needs to be applied to the radiocarbon dates of marine carbonates due to oceanic reservoir effects (Berger *et al.* 1966; Bowman 1985), we have not applied the correction to the radiocarbon dates of this study for the following reasons:

1. the shells of this study are mostly estuarine, and estuarine waters are derived from oceanic, fluvial and meteoric sources. The correction for reservoir effects due to fresh water input draining a Pleistocene limestone hinterland is unknown;

2. the results of Bowman (1985) for southern Australia are based on four samples, and this is not a statistically valid sample number;

3. the results of Bowman (1985) are based on benthos from rocky shores and seagrass environments; until the influences of the environmental, feeding, and physiological differences on the shell secretion of the various shelly benthos are better understood (see Crenshaw 1980, Rhoads 1980, Rosenberg 1980), radiocarbon dates obtained from modern organisms existing in markedly different environments and using different feeding strategies should be treated with caution.

Workers wishing to compare their data with the results of this study, or wishing to use the results of this study in the future can add the correction factor of 480 + 30 (Bowman 1985) to the results of this paper (Table 1) if necessary.

Regional setting

The Peel-Harvey estuary is a compound estuary barred by a Pleistocene barrier ridge of limestone and sand, and is essentially three coalesced estuary systems. The estuarine system is composed of the sub-circular Peel Inlet, which is the receiving basin for the Murray and Serpentine Rivers, the elongate Harvey Estuary, which is the receiving basin for the Murray River; and a narrow linear exchange channel, which connects the estuary with the Indian Ocean and is partly choked by an emergent channel shoal complex and tidal delta (Hodgkin *et al.* 1980). The main regional geomorphic components framing the system are a barrier ridge of Spearwood Dunes to the west, aeolian and fluvial lowlands of Bassendean Dunes and Pinjarra Plain to the east, and riverine discharge points (McArthur & Bettenay 1960).

The Peel-Harvey estuary can be subdivided into sublittoral, littoral, and supralittoral zones, and Brown *et al.* (1980) largely describe the sublittoral and some littoral zones of this system. Semeniuk & Semeniuk (1990) subdivided the littoral and supralittoral into various shore types. These shores encompass modern and stranded Holocene landforms, and Pleistocene landforms and sediments. Each shore type is a product of various estuarine, fluvial, and marine sedimentary processes, resulting in specific sediment types and geometry. Twelve shore types were recognised: tidal shoals, active tidal delta, stranded channel shoal complex, relict tidal delta, stranded estuarine embayments, spit-lagoon complexes, beachridge complexes, marginal platforms, erosional sandy shore, limestone cliff—pocket beach shore, lobate fluvial delta complex, and elongate fluvial delta complex.

Description of coastal landforms and their radiocarbon chronology

In this study, the stratigraphy and chronology of a tidal shoal, a stranded channel shoal complex, a relict tidal delta, a stranded estuarine embayment, a beachridge system, and the lobate delta are described (Figs 1F & 2). Information on each of these landforms (drawn from Semeniuk & Semeniuk 1990) and on the stratigraphy and radiocarbon chronology is presented below.

The position of the transects of Figure 1 in this paper generally correspond with the transect positions illustrated by Semeniuk & Semeniuk (1990), but the stratigraphic transect numbers in this paper do not necessarily correspond with the transect numbers of Semeniuk & Semeniuk (1990). Also transects 2 and 3 of this paper, although they are approximately in the same area as transects 2 and 4 of Semeniuk & Semeniuk (1990), are

Table 1

Description of Material used in Radiocarbon Dating

Sample no. this paper (1)	Field no.	Laboratory no. (2)	Transect No.	Stratigraphic setting	Rationale for sample	Height (m) of SL indicator if applicable (3)	Sample type	Age in ^{14}C yrs BP C13 corrected	d ^{13}C ($^{o}/_{oo}$ PDB)
1	MTDW.0 /3-4 *Katelysia*	GX-12897	2	Middle estuarine shelly sand within stranded channel shoal complex	Age of estuarine sand	—	*Katelysia scalarina*	5300±85	1.1
2	MTDW.0 /9-10 chamiid	GX-12898	2	Top of muddy estuarine sequence within stranded channel shoal complex	Age of estuarine mud	—	*Chama ruderalis*	7445±245	0.7
3	MTDW.0 /9-10 *Katelysia*	GX-12899	2	Top of muddy estuarine sequence within stranded channel shoal complex	Alternative taxonomic replicate for sample (2) above	—	*Katelysia scalarina*	7520±95	–0.1
4	PW7:50cm *Sanguinolaria*	GX-12657	2	Top of shelly estuarine sand within stranded channel shoal complex; shell disarticulated and some in situ.	Age of estuarine sand flat	Shallow sublittoral sand flat facies 1 m above AHD	*Sanguinolaria biradiata*	4240±80	2.5
5	MTDW.1 surface *Katelysia*	GX-12668	2	Shelly mud filling depression at top of channel shoal complex	Age of estuarine surface	Surface is 1.03 m above AHD	*Katelysia scalarina*	4895±85	1.1
6	MTDW.1 /12-13 *Katelysia*	GX-12667	2	Lower muddy estuarine sequence within stranded channel shoal complex	Age of estuarine sequence earlier in the Holocene	—	*Katelysia scalarina*	7670±260	0.5
7	MTDW.1 /14-15	GX-12666	2	Lower muddy estuarine sequence within stranded channel shoal complex	Age of estuarine sequence earlier in the Holocene	—	Mixed shell	8560±470	–1.7
8	PW2:50-70cm *Sanguinolaria*	GX-12662	2	Top of shelly estuarine sand within stranded channel shoal complex; shell disarticulated and some in situ.	Age of estuarine sand flat	Shallow sublittoral sand flat facies 1.5 m above AHD	*Sanguinolaria biradiata*	4400±120	2.1
9	PW2:50-70cm *Katelysia*	GX-12661	2	Top of shelly estuarine sand within stranded channel shoal complex; shell disarticulated and some are in situ.	Age of estuarine sand flat	Shallow sublittoral sand flat facies 1.5 m above AHD	*Katelysia scalarina*	4505±80	0.6
10	PW4: o/c oyster	GX-12659	2	Oyster encrusting small emergent limestone island	Age of oyster encrustation and hence age of marine-estuarine inundation	Shell encrustations are 1.5 m above AHD	*Ostrea angasi*	5390±50	–0.4
11	MTDW.3 /2-3m top *Katelysia*	GX-12665	2	Base of shelly estuarine sand within stranded channel shoal complex; also base of Holocene in this drill site.	Age of estuarine sand	—	*Katelysia scalarina*	6640±200	0.9
12	PW4: o/c chamiid	GX-12660	2	Chamiids encrusting small emergent limestone island	Age of shell encrustation and hence age of marine-estuarine inundation; taxonomic replicate for (10)	Shell encrustations are 1.5m above AHD	*Chama ruderalis*	6130±300	1.7
13	VCSRG MTDW BH2 3.5 m	GX-12540	2	Roots of tree penetrating Pleistocene limestone	Age of estuarine inundation	Root horizon is located 1 m below AHD	Wood	7645±100	–25.0

Table 1—*continued*

Description of Material used in Radiocarbon Dating

Sample no. this paper (1)	Field no.	Laboratory no. (2)	Transect No.	Stratigraphic setting	Rationale for sample	Height (m) of SL indicator if applicable (3)	Sample type	Age in ^{14}C yrs BP C13 corrected	d ^{13}C (°/$_{oo}$ PDB)
14	MTDW.4 /8-9m large *Electroma*	GX-12664	2	Shells within partially cemented Pleistocene limestone	To confirm age of the Pleistocene limestone	—	large species of *Electroma*	>36,600	1.4
15	MTDW.4 /8-9m chamiids	GX-12663	2	Shells within partially cemented Pleistocene limestone	To confirm age of the Pleistocene limestone	—	Chamiids	>38,000	1.8
16	MTDE.5 /0-1m	GX-12669	3	Top of estuarine shelly sand overlying Pleistocene limestone at shallow depth	Age of estuarine sand flat	Surface of sand flat is 1.0 m above AHD	Mixed shell	6420±360	2.0
17	MTDE.5 /2-3m	GX-12670	3	Shells within partially cemented Pleistocene limestone	To confirm age of the Pleistocene limestone	—	Mixed shell	>32,000	1.5
18	MTDE.5 /4-5m	GX-12671	3	Shells within partially cemented Pleistocene limestone	To confirm age of the Pleistocene limestone	—	Mixed shell	>31,000	1.4
19	MTDE.4/5 /1-2m	GX-12672	3	Shells lying on surface of Pleistocene limestone	Age of estuarine shell (see note [4] below)	—	Mixed shell	12530±210	2.6
20	MTDW.3 /0.5-1m *Katelysia*	GX-12673	3	Upper part of shelly estuarine sand flat within relict tidal delta	Age of estuarine sand surface	Surface of sand flat is 0.87m above AHD	*Katelysia scalarina*	4835±185	1.7
21	MTDW.3 /1-1.5m	GX-12674	3	Upper part of shelly estuarine sand flat within relict tidal delta	Age of upper estuarine sand	—	Mixed shell	4500±175	1.9
22	MTDE.3 /4-5m	GX-12675	3	Shelly horizon with muddy sediment fill in channel	Age of channel fill	—	Mixed shell	5695±180	2.2
23	MTDE.2 /0.5-1m *Katelysia*	GX-12676	3	Upper part of shelly estuarine sand flat within relict tidal delta	Age of estuarine sand surface	Surface of sand flat is 1.07m above AHD	*Katelysia scalarina*	4740±80	1.5
24	MTDE.2 /1-2m *Katelysia*	GX-12677	3	Upper part of shelly estuarine sand flat within relict tidal delta	Age of upper estuarine sand	—	*Katelysia scalarina*	5000±190	1.6
25	No.17: Styx Transect A (Spit : wood)	GX-11395	4	Wood buried in tidal mud underlying an eroding spit	Age of surface of muddy tidal shoal	Wood horizon is located c 0.5m above AHD	Wood	–650±105 (contemporary)	–24.6
26	Sample 15. CS/RANGER—C2: peat & sand	GX-11104	6	Peat within buried lagoonal swale within beachridge sequence	Age of peaty lagoonal deposit, and hence age of enclosing beach ridges	Peat unit is 1 m below AHD	Peat	6365±115	–25.5
27	Sample 16. CS/RANGER—C3: 220cm, peat & sand	GX-11105	6	Peaty sand within buried lagoonal swale within beachridge sequence	Age of peaty lagoonal deposit, and hence age of enclosing beach ridges	Peat unit is 2 m below AHD	Peaty sand	6980±120	–27.4
28	VCSRG 22. CDP 4: 5-6m estuarine shell	GX-12021	5	Shells within mud filling an abandoned channel in a deltaic complex	Age of the estuarine channel fill	—	Mixed shell	6015±400	–0.6

Table 1—*continued*

Description of Material used in Radiocarbon Dating

Sample no. this paper (1)	Field no.	Laboratory no. (2)	Transect No.	Stratigraphic setting	Rationale for sample	Height (m) of SL indicator if applicable (3)	Sample type	Age in ^{14}C yrs BP C13 corrected	d ^{13}C (‰ PDB)
29	SSR.0 (NMB)	GX-12622	1	Upper estuarine shelly mud	Age of estuarine sedimentation	Shelly unit is located 2.2 m above AHD	*Katelysia scalarina* & *Sanguinolaria biradiata*	6910±235	–2.1
30	SSR.1 : 7-8m	GX-12623	1	Shelly gravel layer of estuarine species at the base of the Holocene sequence	Age of estuarine sedimentation	—	*Katelysia scalarina* & *Sanguinolaria biradiata*	7050±115	–2.3
31	SSR.3 : 8-9m	GX-12902	1	Shelly beach layer within beach/dune barrier	Age when estuarine conditions were terminated	Shelly unit is located 0.5 m above AHD	Mixed *Donax*, *Glycymeris* & *Donacilla*	3475±160	1.6
32	Mandurah Fossil Island *Katelysia*	GX-10962	3	Shelly layer underlying a small chenier at the edge of a stranded tidal shoal within the relict tidal delta complex	Age of surface of relict tidal delta	—	*Katelysia scalarina*	5930±105	0.6
33	Mandurah: Marsh/Bridge *Katelysia*	GX-10961	near transect 1; see Fig. 1	Shelly layer on surface of former estuarine sand flat	Age of estuarine sand flat	Within 1 m of former sealevel	*Katelysia scalarina*	5780±190	1.2
34	Mandurah: Marsh/Bridge *Sanguinolaria*	GX-10960	near transect 1; see Fig. 1	Shelly layer on surface of former estuarine sand flat	Age of estuarine sand flat; taxonomic replicate for sample (33)	Within 1 m of former sealevel	*Sanguinolaria biradiata*	4340±200	2.3
35	Sample 1: Mandurah Cottage *Sanguinolaria*	GX-11090	near transect 1; see Fig. 1	Shelly layer 0.5m below surface of former estuarine sand flat	Age of estuarine sand flat	Within 1 m of former sealevel	*Sanguinolaria biradiata*	4375±95	2.2
36	PW6: 50cm *Katelysia*	GX-12658	near transect 1; see Fig. 1	Shelly layer 0.5m below surface of former estuarine sand flat	Age of estuarine sand flat	Within 1 m of former sealevel	*Katelysia scalarina*	4355±50	1.1

1. Location of samples are shown in Figures 1 & 2.
2. GX numbers: Kreuger Geochron Laboratories
3. Relative to AHD.
4. Sample appears to be a mixture of Holocene and reworked Pleistocene shell.

composite sections derived from core information, trenches and outcrops located within a transect belt 100-150 m wide; thus the details of sequence and lithology within transects 2 and 3 in this paper differ in some respects from the profiles presented by Semeniuk & Semeniuk (1990).

Tidal shoals

Tidal shoals, situated in the tidal channel, are elongate, oval, sediment bodies, attached to the shore at their southern ends, and aligned with the channel by tidal currents. The shoals have developed as secondary features on the relict tidal delta and cuspate projections of the sandy hinterland, and may be bordered by recurved spits (Fig. 1E). The shoals are underlain by fine and medium sand at depth, and muddy sand and mud in upper parts; a recurved spit facies may occur as a perched thin shoestring (Transect 4, Fig. 2). Radiocarbon analysis of wood excavated from muddy sediment exposed in a small cliff by the eroding, retreating south part of the tidal shoal gave a contemporary age for the upper part of the tidal shoal sequence (Fig. 2). This implies that deposition of the upper part of the shoal to encase the wood, and the subsequent retreat of the barrier spit to bury and later expose the shoal stratigraphy, has occurred in near modern times.

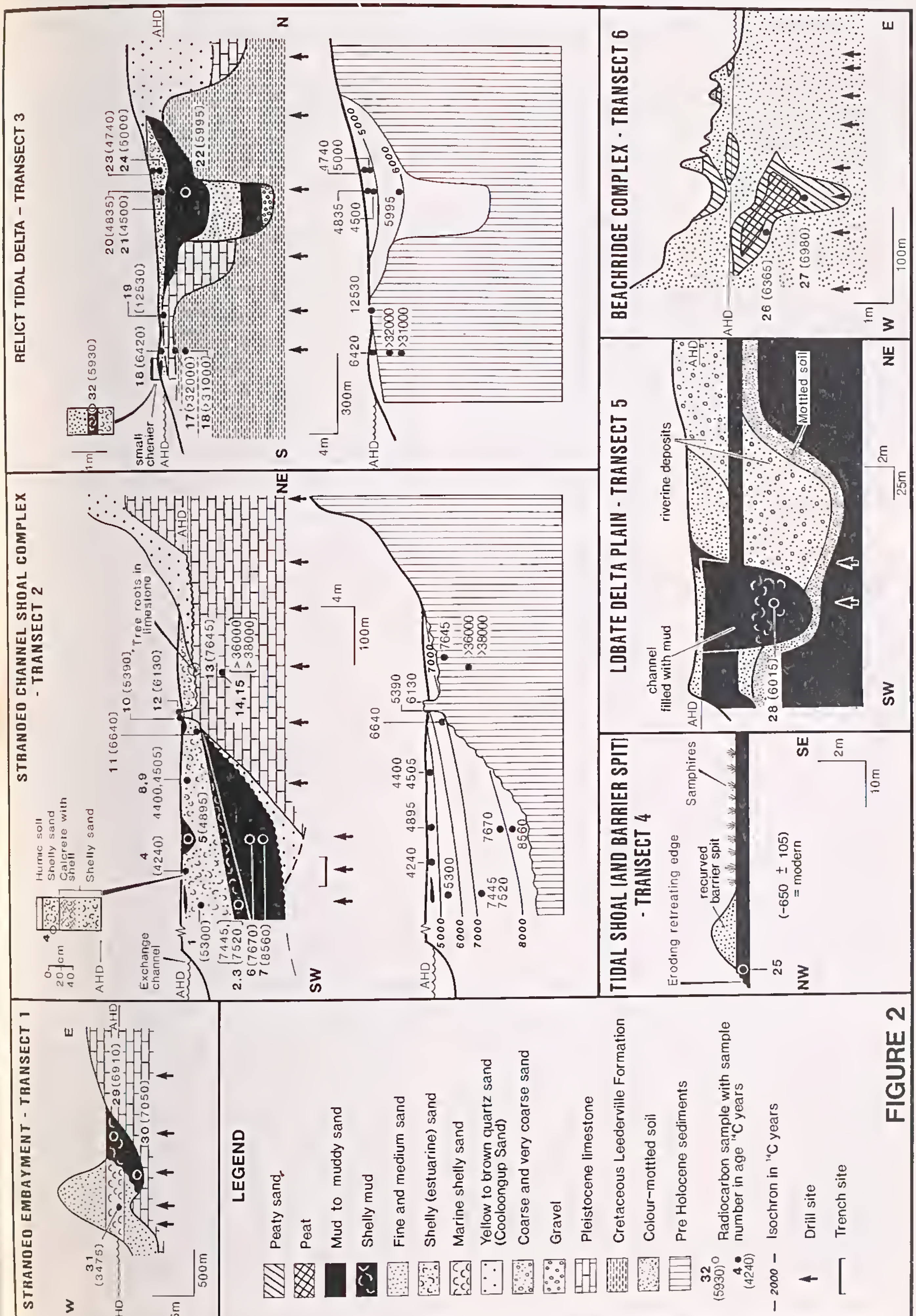

Figure 2 Stratigraphic profiles, location of subsurface sample sites for radiocarbon material, and, where applicable, age structure reconstructions for transects shown in Figure 1.

Stranded channel shoal complex

A stranded, or emergent, channel shoal complex adjoins the modern exchange channel (Fig. 1C). The surface of the landform is comprised of a series of very low relief sand ridges and ellipsoidal sand hummocks (former sand waves and shoals), that are elongated sub-parallel to the former exchange channel margin and are separated by low sinuosity shallow linear depressions and channels. The stranded channel shoal complex at shallow depths is underlain mainly by shelly sand (Transect 2, Fig. 2), similar to modern estuarine sand shoal and sand flat facies, with disarticulated and articulated estuarine shells such as *Sanguinolaria biradiata*, *Katelysia scalarina*, and *Katelysia rhytiphora*, and represents a littoral to shallow sublittoral surface formed when sealevel was relatively 2 m higher earlier in the Holocene. Depressions in the landform are filled with modern sand and mud sheets. At depths greater than 8 m, the sediments consist of channel-fill deposits, with large scale cut-and-fill structures.

Estuarine sand-flat bivalves (samples 4, 5, 8, 9, 34, 35 & 36) analysed for radiocarbon gave ages between c. 4200 and 4900 yr BP for the surface and near-surface of the former estuarine sand flat, thus showing reasonable consistency in the age of this sedimentary surface.

In situ encrustations of oysters and chamiids (samples 10 & 12), located 2 m above present MSL on former, small limestone-rock islands and on limestone pinnacles that gave ages of c. 5400 and c. 6100 yr BP, indicate that sealevel had reached this relative elevation by c. 6100 yr BP. Tree roots embedded in limestone at a level of 1 m below present MSL (sample 13) gave an age of c. 7600 yr BP, and the oldest radiocarbon age for shells, some 14 m below present MSL (sample 7), gave an age of c. 8600 yr BP, indicating that estuarine—marine conditions had established at these levels by c. 7600 and 8600 yr BP, respectively.

The chronology of sediments underlying the stranded channel shoal complex has been determined by drawing isochrons on stratigraphic sections using the available radiocarbon ages within the sequence (Fig. 2). The isochrons show that the sedimentary accumulation formed by upward shoaling processes, commencing c. 8600 yr BP and continuing until c. 4200 yr BP, with some 16 m of sediment accreting in 4000 yrs.

Relict tidal delta

A relict tidal delta, which also formed during a higher sealevel earlier in the Holocene, adjoins the south-east part of the modern exchange channel. The complex is a flat terrain with relict (abandoned, infilled) tidal channels, and emergent shoals, onlapped by sand and shelly sand and mud sheets which fill the depressions (Fig. 1D). The relict shoals exhibit geomorphic patterns such as stranded sand ribbons (low cheniers) on the margins of stranded former shoals, and former erosional scars, illustrating their accretional history from smaller nucleus shoals. The stratigraphy of the relict tidal delta is variable over short distances, with lensoid veneers of sand, shelly sand, and mud disconformably overlying shelly muddy sand, coarse quartz sand, or medium quartz sand, which in turn disconformably overlie an irregular surface of Pleistocene limestone and Cretaceous Leederville Formation. The complex stratigraphy reflects the origin of the terrain that formed by shifting fluvial and tidal channels (with their accompanying erosion and filling) and accreting shoals.

Estuarine, sand-flat bivalves (samples 20, 21, 23, & 24) gave ages between 4500 to 5000 yr BP for much of the surface and near-surface of the relict sand flat of the tidal delta, which formed when relative sealevel stood 2 m higher than present. These datings also show reasonable consistency in the age of this sedimentary surface. Sample 32 from a shell horizon beneath a stranded small chenier bordering the edge of a relict emergent shoal (Transect 3, Fig. 2) gave an age of c. 6000 yr BP, and indicates that the mounds of sediment of the tidal delta complex can be of various ages. The chenier is < 1 m thick and appears as a sand ribbon on the edge of the eroded shoal, and possibly formed when sealevel was falling and the shoals were being exposed. Mixed shell (sample 16), located in sand 1 m above present MSL and overlying a former limestone pavement at shallow depths, gave an age of c. 6400 yr BP, indicating that sealevel had reached this relative height by this time. The oldest Holocene date in the deeper parts of the sequence is sample 22 which gave an age of c. 5700 yr BP within a tidal channel fill deposit. The chronology of the stratigraphy underlying the relict tidal delta is shown in Transect 3 (Fig. 2). The isochrons also imply that the accretion of the tidal delta formed by upward shoaling, commencing at least by c. 5700 yr BP and continuing until c. 4500 yr BP.

Stranded estuarine embayment

A stranded estuarine embayment adjoins the exchange channel, and comprises an elongate estuarine lowland formed behind a barrier dune (Fig. 1B). The lowland is underlain by tidal estuarine deposits (Transect 1, Fig. 2), but was formerly connected to the exchange channel (see fig 12 B,C of Searle *et al.* 1988). The radiocarbon ages and height of the samples relative to AHD (samples 29 & 30) indicate that estuarine conditions were established by c. 7000 yr BP, with relative sealevel 2.2 m higher than at present. Sample 31 within the beach and barrier dune sequence indicates that the estuarine sequence was eroded and estuarine sedimentation terminated in this embayment by c. 3500 yr BP (Searle *et al.* 1988).

Beachridge complex

Beachridges occur extensively along the shore of Peel Inlet and Harvey Estuary, but it is only in the Island Point area where material suitable for dating was found in the sequence. Beachridge complexes are ribbon-shaped and are comprised of low sand ridges and intervening swales (Fig. 1G). Their stratigraphy in the Island Point area is complex, with surface and buried lenses of mud and coastal peat, deposited in swales, interspersed with sand spit/ridge deposits (Transect 6, Fig. 2). All ridges have been eroded by wind and sheet wash so that swales are partly infilled by sand, and capped by humic or peaty soil.

Samples 26 & 27 from within the peat lithofacies of the beachridge stratigraphy gave ages of c. 6400 and 7000 yr BP. The older age is from a layer within a peat and sandy peat lens, that is located 2 m below present MSL. The younger age is from a peat within the same lens but at a level 1 m below present MSL. The peats are coastal peats deposited generally at about sealevel, so these data would indicate peat accumulation with sealevel some 1-2 m below present c. 7000-6400 yrs ago. The ages of the peat deposits are used to infer the age of the containing beachridge sand sequence. Thus the sands under the beachridge complex at this study site appear to have commenced accumulation by c. 7000 yr BP.

Lobate fluvial delta complex

The lobate fluvial delta is the combined delta system of the Serpentine and Murray rivers. Although the delta is a high-constructive lobate type (Fisher *et al.* 1969), wave reworking of the shore has resulted in shore-parallel, low beachridges, separated by inter-ridge swales and flats. The Murray River is the dominant system for transporting sediment and constructing the delta. There is a large deltaic plain adjoining the main channel and distributary channels (Fig. 1F), and this has been subdivided by Semeniuk & Semeniuk (1990) into abandoned channels, levees, lakes (former, abandoned inter-distributary basins), flats, basins, ridges and hummock/swale system (degraded levee system). The stratigraphy of the deltaic plain is variable and complex, depending on formative environment, history, and age of particular units. There are interlayered sheets, lenses and shoestrings of various grain sizes of sand, muddy sand, sandy mud, mud, and at depth, coarse river gravel and gravelly coarse sand (Transect 5, Fig. 2).

Sample 28, comprised of estuarine shells from mud filling an abandoned channel cut into fluvial sands, gave an age of c. 6000 yr BP. This indicates that the bulk of the fluvial system was emplaced prior to that time.

Discussion

The results of this paper are discussed below in terms of 1) evaluation of the radiocarbon dates, 2) variability of ages of shore types, 3) the chronology of some shore types, and 4) the sealevel history recorded in this area.

Evaluation of radiocarbon dates

Many of the shells used in this study are whole and unfragmented *Sanguinolaria biradiata*. In modern estuarine environments such shells usually are rapidly fragmented if transported and reworked, or fragmented by burrowing crustaceans if they are not buried relatively soon after death (Semeniuk MS). In many of the horizons sampled during this study, these shells were found articulated, and some are found *in situ* in the living position. These factors suggest that the shells of *Sanguinolaria biradiata* are not reworked from older deposits, and that they would provide reasonable radiocarbon dates for the containing sediment.

Shells of *Katelysia scalarina* that occur in association with *Sanguinolaria biradiata* also were collected and dated and provided radiocarbon dates that were generally similar to *Sanguinolaria biradiata*, implying again that there has been little or no reworking of these shells. *In situ* shells of oysters and chamiids that are encrusting limestone pinnacles and islands provide direct evidence of the lack of reworking of these encrusting benthos. The lenses of peat and peaty sand within the beachridge sequences also provide direct evidence of *in situ* accumulations.

Only the mixed shell assemblages in this study are potentially problematical as to whether they are reworked accumulations (ie, mixtures of autochthonous shell and extraneous older shell) or reasonably autochthonous accumulations composed of biogenically fragmented shell. Six samples of mixed shell were used in this study. Five of the mixed shell samples (samples 7, 16, 21, 22 and 28) are wholly within the estuarine sediment sequence. The results from these mixed shell samples (Fig. 2) indicate that the radiocarbon date that each returned is in general agreement with the trends and patterns of the isochrons, and depth below AHD, as determined by the other monospecific and/or encrusting shell material described above. For instance, compare the results of the mixed shell sample 7 with the trends determined by monospecific shell samples 2, 3 and 6 in transect 2.

The sixth sample, sample 19, was comprised of shell fragments resting directly on the unconformity surface cut into fossiliferous Pleistocene limestone. The sample returned an age of c 12500 yr BP for the unconformity surface that has been dated by samples 10, 11 and 12 as c 5400-6600 yr BP. It appears, therefore, that sample 19 is a mixture of fragmented Holocene shell and remanie fossil grit reworked from the underlying Pleistocene limestone.

Variability of ages of the shore types

A wide range of shore types comprise the Peel-Harvey estuarine system, and these coastal landforms are of various ages. Some began forming as early as c. 7000 yr BP, when the sea first flooded the estuary. Other landforms are relatively young, ie, less than 1000 yr BP. Clearly the development of the coastal landforms, and hence the associated wetlands and their vegetation have not formed synchronously throughout the estuary. Some of the features are long term relict, formed with relative sealevel at higher positions, while others are comparatively recent. The ages of some of the Holocene deposits at the various study sites imply antiquity for some of the estuarine coastal landforms. That is, some of the coastal landforms may in fact be older, relict features, with very little accumulation and landform development occurring today (eg, the stranded channel shoal complex and the relict tidal delta). Some of the landforms may be pre-Holocene; for instance, the age of c. 6000 yr BP for deposits filling channels incised into fluvial facies of the lobate delta imply that the fluvial deposits may have been emplaced before Holocene sealevels reached their present position. Further research, however, is required to support this hypothesis, and will be reported in future studies.

Chronology of some shore types

This paper provides chronological reconstructions for estuarine stratigraphic sequences for the first time in Western Australia, and provides information on the pattern of sedimentary accretion in channel-shoal and tidal-delta settings. Where data are available, the chronology of the estuarine channel shoal and tidal delta accumulations suggests that a large component of their accretion involved upward shoaling, rather than lateral progradation. Beachridge sequences, on the other hand, exhibit by their geomorphology clear evidence of accretion by lateral progradation. The data also show that the sequences accrete sediment relatively rapidly, ie 4-8 m in 4000 years.

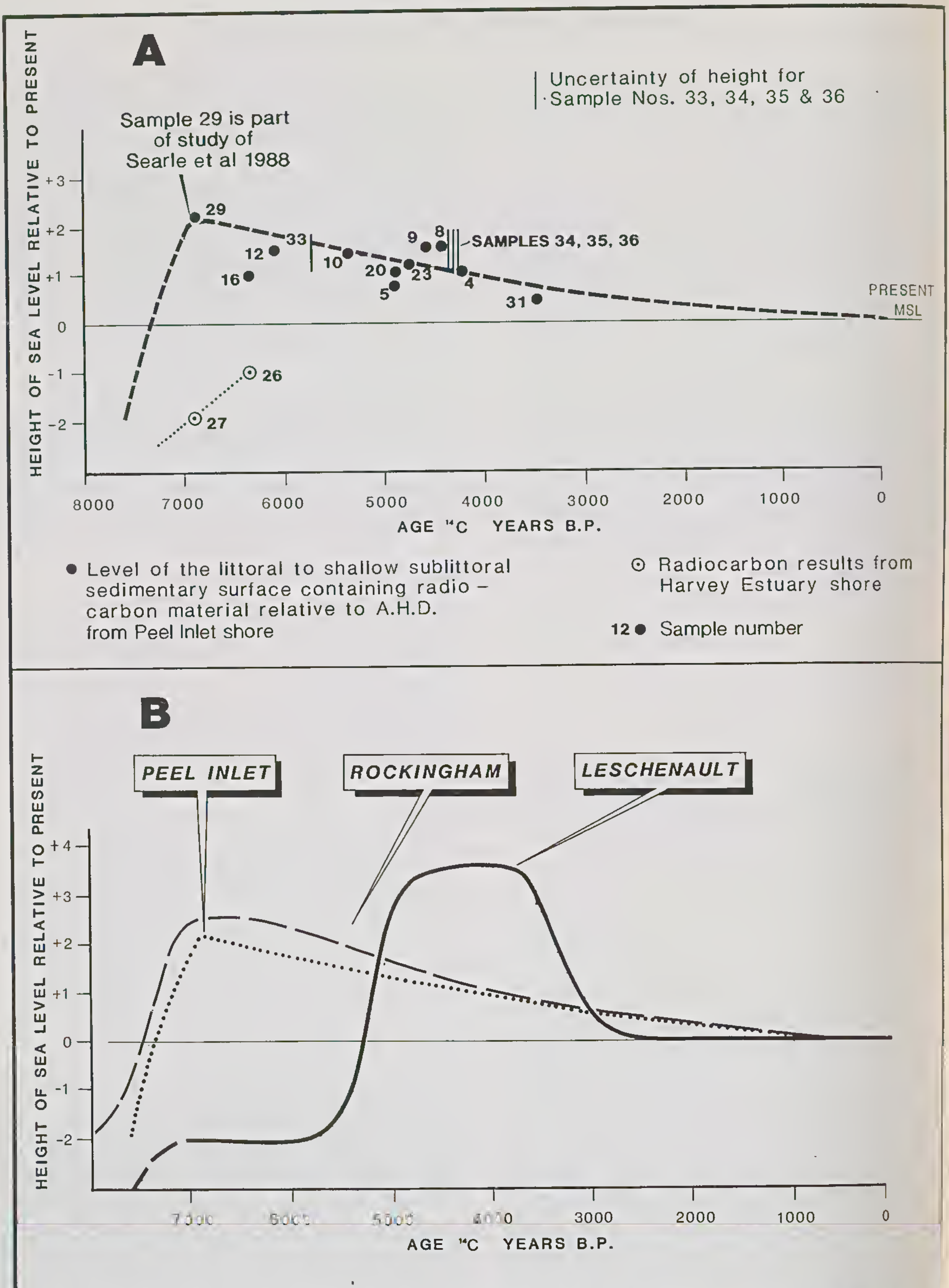

FIGURE 3

Figure 3 A Sealevel history curve for the Peel-Harvey estuary. B Sealevel history curve for the Peel-Harvey estuary compared to sealevel history of the Leschenault Peninsula and Rockingham-Becher areas (after Semeniuk & Searle 1986). Note that the curve from Searle *et al.* 1988 has had the reservoir correction factor removed to make it comparable with the curves of this study and with Semeniuk 1985. The radiocarbon results of Semeniuk 1985 had not been corrected by Semeniuk for oceanic reservoir effects because that study too was based mainly on estuarine shell.

Sealevel history

Sealevel history recorded in this area shows that in southern parts of the estuary, in the Harvey Estuary system, relative sealevel stood at 1-2 m *below* present MSL some 6400 and 7000 yr BP. The position of relative sealevel at this time is similar to that recorded in the Leschenault Peninsula barrier dune system (Semeniuk 1985). However, in the north of the estuarine system, ie in Peel Inlet, around 7000 to 6100 yr BP, and later, relative sealevel stood about 1.5-2 m *above* present. The position of relative sealevel at this time is similar to that recorded in the Rockingham-Becher beachridge plain (Searle *et al.* 1988). The other radiocarbon ages and sealevel indicators obtained from the northern estuary settings appear to conform to a falling sealevel curve from c. 6500 yr BP to the present. The resultant curve is similar to the established sealevel history curve for the Rockingham-Becher area (Fig. 3), but not similar to those for the Leschenault Peninsula (Semeniuk 1985) and Rottnest Island (Playford 1988). The results above suggest that the tectonic factors invoked to explain marked variation in sealevel history along the southwestern Australian coast (Semeniuk & Searle 1986) may also explain the variation of relative sealevel history in the Peel-Harvey estuarine system. On this basis, at this stage, it would seem preferable to construct sealevel history curves separately for the Peel Inlet sequences and the Harvey Estuary sequences.

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The epizoic diatom *Falcula hyalina* Takano on a pelagic copepod from the Swan River estuary, Western Australia

Jacob John

School of Biology, Curtin University of Technology
Bentley, WA 6102

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Abstract

The diatom *Falcula hyalina* Takano growing attached to the copepod *Sulcanus conflictus* is recorded from the Swan River estuary. This is the first record of an epizoic diatom in Australia. The morphology, ultrastructure, taxonomic status and known geographical distribution and ecology of the diatom are discussed.

Introduction

Many diatoms grow attached to seaweeds, clams, rocks, shells, sediments and even the skin of dolphins and whales. Diatoms growing attached to pelagic copepods are relatively rare (Simonsen 1970). Such associations between diatoms and copepods are often host-specific and speculated to be symbiotic (Ikeda 1977). One such diatom is *Falcula hyalina* Takano reported to be growing attached to different species of calanoid copepods (Takano 1983, Hiromi et al 1985, Prasad *et al.* 1989).

Voigt (1960:61) established the araphid genus *Falcula* and described the four species, *F. rogallii*, *F. media*, *F. semiundulata*, and *F. paracelsiana*. These species were epiphytes, characterized by a sinuous apical axis and an eccentric axial area arranged closer to the ventral margin of the valve. Voigt remarked that the genus *Falcula* was related to *Synedra* and *Pseudohimantidium*. Simonsen (1970) established the family Protoraphidaceae to include *Protoraphis* and *Pseudohimantidium*, both of which tend to show apical rows of labiate processes on each pole and are predominantly epizoic (Gibson 1979).

The present species of diatom was first encountered as growing attached to the calanoid copepod *Sulcanus conflictus* in the Swan River estuary in 1981 and its ultrastructure investigated (John 1984). However, Takano found it epizoic on the calanoid copepod *Acartia steueri* in the coastal waters of Shimoga City and described it as *Falcula hyalina* in 1983. The genus *Falcula* has provoked a great deal of interest among diatomists, due to its apparent resemblance to eunotoid diatoms (Round & Sims 1979). Because information on epizoic diatoms is generally sparse, it is worthwhile reporting the occurrence of an epizoic diatom from Australia, for the first time. This paper also deals with some aspects of the taxonomic status and distribution of *Falcula hyalina*.

Materials and Methods

During an extensive survey of the Swan River estuary (31°45'S, 116°04'E) plankton samples were collected using a net of 45 µm mesh in 1980-81. The hydrology and physico-chemical properties of the Swan River estuary were presented in John (1983: 84 & 87). Copepods collected were examined and *Sulcanus conflictus* infested with *Falcula hyalina* were photographed using a Nikon photomicroscope. The epizoic diatoms washed from the copepod were cleaned and examined by light, and scanning electron microscopy as described by John (1983).

Observations and Discussion

The posterior metasome, urosome and the furcal rami of the copepod *Sulcanus conflictus* were infested with the diatom (Fig. 1A). The frustules were attached to the copepod by one end in clusters (Fig. 1B). The cells were very thinly silicified and delicate with two plate-like light green chromatophores in each cell (Fig. 1C).

Valves are arcuate, linear with obtuse apices. The dorsal margin is broadly convex and ventral margin slightly concave. The axial area is broad, not clearly defined and located closer to the ventral margin. The valve face is striate; striae areolate and difficult to resolve under light microscope. The areolae become increasingly smaller towards the axial area (Figs. 1 D,E,F)

SEM studies (Fig. 1G) reveal that there is a small, deeply set porefield on each pole of both valves. A distinct labiate process is also present, but only on one pole of each valve (Fig. 1D) The labiate processes are located on alternate poles of the two valves of the frustule. The labiate process opens externally by a circular pore and is developed into a small lip-structure internally, with its slit oriented

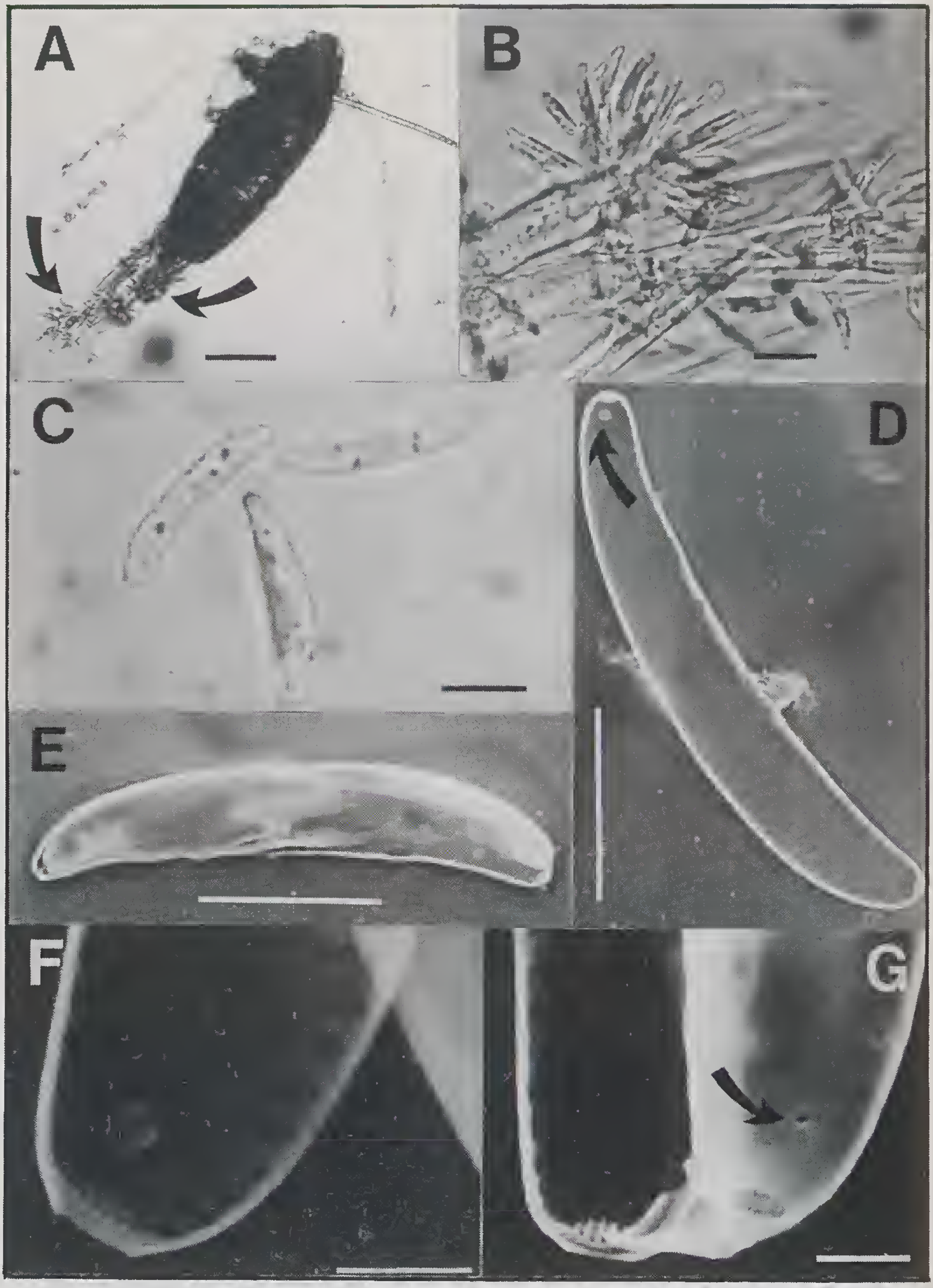

Figure 1 **A** Light micrograph. *Sulcanus conflictus* infested with the epizoic diatom *Falcula hyalina* (arrow points to the furcal rami of the copepod). Scale bar = 100 µm. **B** Light micrograph. Clusters of diatoms attached to the urosome and furcal rami of the copepod. Scale bar = 10 µm. **C** Light micrograph. Fresh frustules showing chromatophores. Scale bar = 10 µm. **D** Scanning electron micrograph (SEM). Internal surface view of valve showing the labiate process on one pole (arrow). Scale = 10 µm. **E** SEM. Whole frustule. Scale = 1 µm. **F** SEM. Internal structure of the areolae, the labiate process and the porefield. Scale = 1µm. **G** SEM. Apex of a frustule showing the porefields of both valves and external opening of the labiate process on one valve. Scale = 1µm.

transapically or obliquely (Figs. 1F,G). Areolae are shallow and small. Length 20-30 µm, breadth 2.7-4 µm, striae 22-24 in 10 µm, areolae 6-7 per µm and apical pores 6-8 per µm.

The features described above suggest that *Falcula* can be considered as a valid genus in its own right and is not closely related to *Protoraphis* and *Pseudohimantidium*, as the latter two genera have labiate processes totally different in structure from that of *Falcula* (Simonsen 1970, Gibson 1979). It appears to be closely related to *Synedra*, and *Hannaea* - a genus established by Patrick (1966). *Falcula hyalina* is very similar to *Synedra* in the mode of attachment to the substrate, labiate process and polar porefields. However, the sinuate apical axis, and the highly eccentric and broad axial area distinguish it from *Synedra*. Its resemblance to *Hannaea* due to the presence of a sinuate apical axis is striking. However, ultrastructural studies on the latter are required to draw further comparison. It is evident that the resemblance of *Falcula* to any eunotoid diatom is only superficial. Similar studies on other species of *Falcula* may clarify this point further.

Though this is the first epizoic diatom reported from Australia, it is of wider distribution. Reimer and Mahoney of the Academy of Natural Sciences, Philadelphia have collected this species from the Indian River, on the east coast of Florida, USA and have also investigated its ultrastructure prior to the publication of Takano's description of the species (Reimer, pers comm). They found it epizoic on *Acartia tonsa*. Recently this species has been reported from Choitawhatchee Bay, north eastern Gulf of Mexico epizoic on *Acartia tonsa*. (Prasad *et al.* 1989).

Takano (1983) collected *Acartia steueri* infested with *Falcula hyalina* in 1982 from the waters of Shimoga City, Japan. Hiromi *et al.* (1985) further recorded this diatom epizoic on *Acartia plumosa* and on species of *Oithona* in Lake Hamako and Mikawa Bay Japan. In all the above cases the copepods were found infested with the diatom only towards the end of the growing season in summer. It is interesting to note that in the Swan River estuary, Western Australia, *F. hyalina* was found only on *Sulcanus conflictus* and not on the other two calanoid copepods -*Acartia clausi* and *Gladioferens imparipes* present in the Swan River. But the infestation occurred only during the autumn season from April to May at the time of the decline of the copepod population. It is reasonable to assume that the source of infestation might be the sediment. The infested copepods were found in the shallow upper reaches of the Swan River within the temperature range of 19-25°C and a salinity range of 19-30 ppt.

The sediments collected at the time of collection of infested copepod had a sparse distribution of *F. hyalina*. However a detailed examination of the sediments before and after the infestation of the copepods failed to locate any specimen of the diatom. Locating this delicate species in the sediment might be difficult. The habitat of the diatom apart from its epizoic episode remains unknown. From the known habitat of this species, it appears to be host-specific. The adult copepods staying at the bottom of the water during the day (Rippingale & Hodgkin 1974) might provide ample opportunity for the diatom in the sediment to become attached to the copepod. Once infested, the diatoms might multiply fast, and the movement of the host might be beneficial to the epizoic diatom for nutrient availability. On the other hand heavy infestation could impair the ability of the copepod to move and may hasten the decline of their population.

Whether the association is symbiotic-mutually beneficial - or a case of infestation detrimental to the host, is difficult to assess at this stage. Only further investigation on the mode of infestation and other habitats of the diatom can resolve this problem.

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The early evolution of the plant life of South-western Australia: comment

G J Retallack

Department of Geological Sciences, University of Oregon, Eugene, Oregon USA 97403

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In a recent presidential address, Beard (1989) suggested that "it was only with the coming of Angiosperms ..... that the entire surface of the earth could be colonized for the first time and a complete plant cover established." As Beard notes in his discussion of my work on reconstructing Triassic vegetation, there is no clear evidence for or against this proposition from fossil plants alone. Nor can there be. As is well known, fossil plants are seldom preserved in place in upland soils because they decay aerobically and are rarely buried in such environments (Retallack 1984). The critical evidence for Beard's hypothesis is not fossil plants, but the paleosols in which they grew. On these grounds, Beard's hypothesis is easily falsified. There are many published reports of red, highly oxidized Triassic paleosols of well drained and upland habitats, and many of these paleosols show abundant root traces and soil horizons typical for soils formed under woodland (Ortlam 1972, Retallack 1976, 1977, Kraus & Middleton 1987, Blodgett 1988, Martins & Pfefferkorn, 1988). It was the paleosols that were the basis for my reconstructions of vegetation and habitats during Triassic time, not the fragmentary remains of plants in local lowland deposits.

The problem of the advent through geological time of woodland and forest cover of well drained soils is only now beginning to be tackled from the perspective of paleosols. Root traces and soil horizons typical under woodlands are found in paleosols of alluvial bottomlands and semi-arid floodplains of Late Devonian age (Retallack 1985). Such stout root traces and thick horizons are found in nutrient-poor silica sands of deltas and in kaolinitic clays of karstified uplands no earlier than mid-Carboniferous (Retallack 1986). Thus there may be some merit to Beard's suggestion that woodland cover was at first in favourable habitats and later spread to habitats difficult because of excessive drainage or low nutrient levels, but all this happened long before angiosperms.

With regard to angiosperms, I can find no inkling that Hughes (1973) regarded them as mangroves during the Cretaceous, as stated by Beard. There were some mid-Cretaceous angiosperm mangroves (Retallack & Dilcher 1981a,b), but most of the early Cretaceous angiosperms were weedy coastal plants other than mangroves (Retallack & Dilcher 1986). In North America, mid-Cretaceous angiosperm megafossils are found in river, lake, swamp and coastal deposits and paleosols. However, associated deep marine and lacustrine deposits have pollen assemblages dominated by conifers. The abundant kaolinitic, nutrient-poor, densely-rooted paleosols of uplands probably were forested mainly by conifers (Retallack & Dilcher 1986). Thus the angiosperms were early successional colonizers of disturbed river banks and beach ridges, not stress-tolerant colonizers of barren uplands. Although one would expect angiosperms to have had a great effect on terrestrial weathering (Knoll & James 1987), Cretaceous paleosols now known are not discernibly different from those of Jurassic or early Tertiary age (Retallack 1986). Claims for the distinctiveness of angiosperms underestimate what is now known about the biological sophistication of seed ferns (Retallack & Dilcher 1988). The appearance of grassland paleosols, with their distinctive granular surface horizon, signals a new and important kind of angiospermous vegetation during the Oligocene and Miocene, but grasslands appear to have been interpolated between and displaced pre-existing wooded shrublands and dry woodlands (Retallack 1990). These and other hypotheses about where plants lived in the distant geological past should not be based entirely on paleobotanical evidence, but rely on increasingly sophisticated analyses of the ancient soils in which they grew.

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The early evolution of the plant life of South-western Australia

Reply by author J S Beard to comment by J Retallack

Dr Retallack's work on paleosols is well known and offers important contributions to our understanding of the plant life and habitats of earlier geological periods. I did not refer to it in my address because it did not seem to me, at the stage which it has reached, to give us significant evidence specifically on upland biota. The reason is this, that if a soil profile is to be preserved and not eroded away it must be buried by transported material of some kind. Almost always this comprises layers of sediment, and for these to be laid down the paleosol must have formed in a depositional sedimentary environment, and cannot have been a remote upland soil of the kind we are discussing. It is difficult to see how soils of the latter type could ever become buried by sediment; but they could of course be buried by aeolian deposits or volcanic eruptions, and if we are able to look for more evidence in this controversy, this surely is where our energies should be directed. If my theory is to be proved wrong we have to find a pre-Angiosperm flora growing on a dry inhospitable upland substrate.

Even then we shall not have reached a definite conclusion. While the existence of aeolian deposits is *prima facie* evidence for an arid climate, we would have to examine the fossil material for evidence of its xeromorphic character; in other words, was it really growing on a "dry inhospitable upland substrate". Numerous authors have commented on the lack of xeromorphy in Mesozoic gymnosperms and the evolution of such characters in gymnosperms later during the Tertiary.

I have seen a paleosol containing charcoal beneath a Pliocene lava flow in Victoria, and numerous examples of soil profiles buried by successive layers of volcanic ash in the Caribbean islands. These cases however are not of sufficient antiquity. Plumstead (1969) recorded in South Africa that a fossilized forest originally growing in the uppermost Cave Sandstone (Triassic) and buried by the basal Drakensberg lavas (Jurassic) could be traced over a distance of 2.4 km, but she identified no components. As this might very well be a case of a genuine upland palesol I endeavoured to obtain further information but without success. Material had been extracted and sent to Paris for examination but there the trail ended. This is Dr Retallack's field and I suggest he might like to arrange a visit to South Africa to locate the site.

I evidently gave the wrong reference to Hughes' halophyte theory, but in any case neither he nor I said that early Angiosperms were mangroves. The expression was that "mangrove environments were critical to their dispersal and succession as they moved to upland sites and disturbed areas along edges of stream valleys and coasts". This is essentially the same view as Retallack & Dilcher in their "Cretaceous Angiosperm Invasion of North America" (1986).

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The ants of a vine thicket near Broome: a comparison with the northwest Kimberley

Alan N Andersen[1] & Allan H Burbidge[2]

[1]Division of Wildlife and Ecology, CSIRO Tropical Ecosystems Research Centre,
PMB 44 Winnellie, NT 0821
[2]Wildlife Research Centre, WA Dept Conservation and Land Management,
PO Box 51 Wanneroo, WA 6065

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Abstract

A vine thicket located 3 km NW of Broome is the most southerly 'rainforest' habitat in Western Australia, and is therefore of considerable biogeographic interest. Its ant fauna was sampled with pitfall traps following the procedure used by Andersen and Majer (in press) at 8 vine thickets in the northwest Kimberley region. A total of 23 species were recorded, with the tropical tramp species *Paratrechina longicornis* comprising 55% of total captures. As was the case in the northwest Kimberley, arid-adapted taxa of the surrounding savanna (*eg* species of *Iridomyrmex, Melophorus, Meranoplus*) were poorly represented, and two unspecialized functional groups ('opportunists' and 'generalized myrmicines') predominated. Compared with the ants of related habitats in the northwest Kimberley, those of the Broome vine thicket appear to have little biogeographic significance, and the predominance of *P. longicornis* is indicative of a high degree of habitat disturbance. These features reflect both the extreme southerly location of the thicket and its close proximity to human settlement, and serve as a basis for predicting the kinds of changes likely to occur following disturbance in other vine thickets of the Kimberley region.

Introduction

In Western Australia, tropical rainforest vegetation is represented by small vine thickets scattered throughout that part of the seasonally arid Kimberley region where mean annual rainfall exceeds 500 mm. They are primarily on sites holding permanent water, or on sheltered rocky slopes, particularly at the bases of cliffs and plateaus (Stoneman *et al.* in press). The thickets are dominated by broad-leaved tree and vine species occurring in the humid rainforests of northeast Queensland. These rainforest islands occur in a vast sea of savanna and sclerophyll woodland, and this, combined with their huge distance from 'mainland' formations on the eastern coast, makes them of considerable biogeographic interest.

Few vertebrate species appear to be locally restricted to vine thickets (Friend *et al.* in press, Johnstone & Burbidge in press, Kendrick & Rolfe in press), but the invertebrate fauna of these habitats is of special significance. For example, of the 119 land snail species recorded from Kimberley vine thickets, 51 are known only from these habitats, and many appear to have extremely restricted distributions (Solem in press). All 26 species of pseudoscorpions collected during a recent survey of Kimberley vine thickets were undescribed (Harvey in press), and included a family (Feaellidae) previously recorded only from rainforests of Africa and India (Harvey 1989). In an intensive study of the ant faunas of eight vine thickets in the northwest Kimberley region, Andersen & Majer (in press) recorded many taxa characteristic of tropical rainforests, including certain species of *Cerapachys, Leptogenys, Cardiocondyla* and *Polyrhachis*, which were absent from surrounding habitats.

Here we describe the ant fauna of a vine thicket on the outskirts of Broome, and compare it with those recorded by Andersen & Majer in the northwest Kimberley. The Broome vine thicket has two special features. First, it is the most southerly of all known such habitats, located about 20 km from the nearest thicket, and about 300 km from where such thickets are common. Second, it suffers from obvious signs of disturbance, including cattle grazing, burning, and rubbish dumping, associated with its close proximity to human settlement.

Methods

The vine thicket is located 3 km NW of Broome, and occupies a total area of about 10 ha. It is long and thin in shape, lying just behind and parallel with the dunes fringing Gantheaume Bay. All but about 2 ha is very open and patchy, with canopy cover being extremely variable and having many gaps. About 30 perennial plant species are known from the thicket, with the common ones including *Lysiphyllum cunninghamii* (Caesalpiniaceae), *Terminalia ferdinandiana* (Combretaceae) and *Pouteria sericea* (Sapotaceae). *Passiflora foetida* (Passifloraceae), a weedy species characteristic of disturbed sites in tropical Australia, is present. Litter depth varies up to 2 cm, with many bare patches. At the time of sampling, both litter and soil were dry, at least to a depth of 20 cm. The thicket occurs on both pale grey coastal calcareous dune sand, and on the red aeolian sand immediately inland. The study area was located on the latter soil type, near its boundary with dune sand.

Ants were sampled with pitfall traps, following the trapping procedure used by Andersen & Majer. Traps (4.2 cm diameter, partly filled with ethanol as a preservative) were spaced 5 m apart and arranged along two perpendicular 50 m transects. They were operated for a 48 hr period during late June 1988 (compared with 72 hr periods during early to mid-June 1988 for the northwest Kimberley study). One trap was unable to be found, so that data are available for 19 rather than 20 traps.

Ants were sorted to species level but, as is the case throughout northern Australia, most could not be identified with certainty. Unidentified species were therefore allocated code numbers, which follow and extend those used by Andersen & Majer. A full collection of voucher specimens is held by the senior author, and an incomplete collection is lodged in the Western Australian Museum.

The biogeographical affinity of each species was determined according to whether the distributions of related taxa are centred in tropical (Torresian distribution), arid (Eyrean) or cool-temperate (Bassian) regions, or are widespread. These determinations were based on the senior author's understanding of the Australian ant fauna, as no comprehensive biogeographic treatment of the fauna has been published. Ant community organization was investigated by assigning species to functional groups based on their habitat requirements and their competitive interactions, as outlined by Andersen & Majer.

Results and Discussion

Species Composition

A total of 23 ant species were recorded in traps (Table 1), with the richest genera being *Monomorium* (6 species), *Paratrechina* (3), *Iridomyrmex* (3) and *Rhytidoponera* (3). The tramp species *Paratrechina longicornis* was by far the most abundant ant (recorded in all but one trap, representing 55% total ants), with *Monomorium* spp., *Solenopsis* sp., *Rhytidoponera* sp. *aurata* gp and another species of *Paratrechina* also commonly recorded (Table 1).

Although the Broome thicket is relatively rich in species, only five are among those (n=102) recorded by Andersen & Majer (in press) in vine thickets of the northwest Kimberley. Moreover, the biogeographical profile of the Broome vine thicket fauna differs markedly from that recorded by Andersen & Majer (Table 2). In the northwest Kimberley, 54% of vine thicket species have Torresian affinities, compared with only 22% in Broome. Conversely, 26% of Broome species belong to Eyrean taxa, compared with only 7% in the northwest Kimberley. Indeed, the biogeographical profile of the Broome vine thicket fauna is remarkably similar to that of savanna habitats of the Kakadu region of the Northern Territory (Table 2).

Table 1

Ant species recorded in pitfall traps in the Broome vine thicket. The biogeographical affinity (T = Torresian, E = Eyrean, B = Bassian, W = Widespread) of each species is given. Numbers are total ants in traps, with frequency of occurrence (n = 19) in brackets.

Taxon	Biogeography	Records
Subfamily Ponerinae		
* *Odontomachus ruficeps*	T	1 (1)
Rhytidoponera sp. nr. *reticulata*	E	3 (2)
Rhytidoponera sp. *convexa* gp	E	5 (4)
Rhytidoponera sp. nr. *aurata*	E	18 (6)
Subfamily Myrmicinae		
* *Monomorium* sp. A1	W	41 (7)
Monomorium sp. A4	W	1 (1)
Monomorium sp. A5	W	5 (3)
* *Monomorium* sp. B3	W	9 (4)
Monomorium sp. B5	W	46 (5)
Monomorium sp. C	W	11 (2)
* *Solenopsis* sp. A	W	25 (6)
Solenopsis sp. C	W	2 (1)
Tetramorium sp. *spininode* gp.	E	1 (1)
Subfamily Dolichoderinae		
Iridomyrmex sp. *nitidus* gp.	W	2 (2)
Iridomyrmex sp. A2	T	7 (3)
Iridomyrmex sp. B2	W	2 (2)
Subfamily Formicinae		
Camponotus sp. A4	T	10 (6)
Camponotus sp. *discors* gp.	W	1 (1)
Melophorus sp. A	E	1 (1)
Paratrechina sp. *minutula* gp. C	E	1 (1)
Paratrechina sp. A3	T	24 (5)
* *P. longicornis*	T	260 (18)
Polyrhachis sp. *inconspicua* gp.	B	1 (1)
	Total	477 (83)

* Species recorded by Andersen & Majer (in press) in vine thickets of the northwest Kimberley region.

Of the five Torresian species recorded in the present study, *P.longicornis* occurs throughout the tropics where it is characteristic of anthropogenic habitats (Wilson & Taylor 1967), and the others are widely distributed in savanna and woodland habitats of northwestern Australia (A N Andersen, unpubl). None of the species can therefore be considered characteristic of tropical rainforests, unlike the situation in the northwest Kimberley (Andersen & Majer in press). It is noteworthy that the southern limit of distribution on the west coast of the green tree ant, *Oecophylla smaragdina*, is at Broome (Lokkers 1986). This species is a dominant ant in vine thickets of the northwest Kimberley, but was not recorded in the present study, nor has it been observed by B Wells or P Foulkes (pers comm) who have considerable familiarity with the thicket.

Table 2

Biogeographical affinities of species recorded in the Broome vine thicket, compared with those of vine thickets in the northwest Kimberley (Andersen & Majer in press) and those of mostly savanna habitats in Kakadu National Park (Greenslade 1985). Numbers represent percentage total species (n = 23, 102 and 104 respectively).

	Broome	Northwest Kimberley	Kakadu
Torresian	22	55	20
Eyrean	26	2	22
Bassian	4	5	5
Widespread	48	38	53

Community Organization

While the species composition differs, the broad pattern of ant community organization (Table 3) in the Broome vine thicket is similar to that recorded in the northwest Kimberley study. Dominant *Iridomyrmex*, ground-foraging subordinate species, and hot-climate specialists were all poorly represented. These are all arid-adapted taxa that are patchily distributed within vine thickets of the Kimberley region, and often are only locally common within canopy gaps. Opportunists and generalized myrmicines comprised the large majority (90% in Broome, average of 77% in the northwest Kimberley) of total ants. The predominance of these unspecialized species presumably reflects the lack of competition from arid-adapted taxa, especially species of *Iridomyrmex* (Andersen & Majer in press).

The most striking feature of the Broome ant community is the predominance of *P. longicornis*, which represented 55% of total ants recorded in traps. The species is locally abundant in anthropogenic and other disturbed habitats throughout sub-coastal northern Australia (eg Andersen 1990), but has never been observed to be abundant in other habitats (A N Andersen unpub obs). In the northwest Kimberley study, it was only recorded in a single trap at a single site. Its extreme abundance at the Broome site is therefore a clear reflection of habitat disturbance.

Conclusion

More intensive sampling, particularly within litter and on vegetation, might reveal that some ant species characteristic of tropical rainforests do occur in the Broome vine thicket. However their absence from pitfall traps, combined with the general biogeographical profile of the species recorded, suggest that the ant fauna of the thicket has little biogeographic significance when compared with related habitats in the northwest Kimberley. Moreover, the predominance of *P. longicornis* indicates that the ant fauna has been seriously disturbed. These features reflect both the extreme southerly location of the thicket, and the high level of disturbance due to its close proximity to human settlement.

Table 3

Ant community organization in the Broome vine thicket compared with vine thickets of the northwest Kimberley (Andersen & Majer in press). Ant species are classified into functional groups (see text), and data are percentage abundance in pitfall traps (+ present, but < 1%).

Functional group/taxon	Broome	Northwest Kimberley mean (range)
Dominant species		
Iridomyrmex	2	1 (0 - 7)
Oecophylla	0	4 (1 -16)
sub-total	2	5 (1 -16)
Associated subordinate species		
Camponotus	2	1 (0 - 4)
Polyrhachis	+	1 (0 - 4)
other	0	+ (0 - 1)
sub-total	2	2 (0 - 4)
Hot climate specialists		
Melophorus	+	0
other	0	7 (1 -17)
sub-total	+	7 (1 -17)
Cryptic species		
Paratrechina sp. *minutula* gp	+	4 (1 -17)
Solenopsis	5	3 (0 -15)
other	0	2 (0 - 4)
sub-total	5	9 (1 -36)
Opportunists		
Odontomachus	+	5 (1 -14)
Paratrechina	60	4 (0 -14)
Rhytidoponera	6	2 (1 - 8)
Tetramorium	+	14 (1 -51)
other	0	2 (0 - 9)
sub-total	66	27 (5 -81)
Generalized myrmicines		
Monomorium	24	17 (0 -35)
other	0	33 (0 -78)
sub-total	24	50 (9 -78)
Total no. species in traps	23	16 (11-24)
Total no. ants in traps	477	225(69-336)

Although this study is based on only one site, the results are of value in predicting the kinds of changes likely to occur in ant communities following disturbance in other vine thickets of the Kimberley region - namely incursions of arid-adapted species from the surrounding savannas, and of tropical tramp species. Together with the results of Andersen & Majer (in press), they provide a framework within which to assess the results of any future monitoring of ant communities in these special habitats. Moreover, because ants integrate a particularly broad range of environmental variables (Andersen 1990), they are likely to provide a useful general indication of the status of the habitat in which they live. We predict that the biogeographic profile and level of disturbance shown by the ant fauna is matched by other faunal groups. To date, detailed data are available only for birds (Johnstone & Burbidge in press, B Wells & G Hooper pers comm), and these are consistent with our prediction. Unlike the situation in the northwest Kimberley, the avifauna contains no rainforest specialists such as the Scrubfowl (*Megapodius reinwardt*), Rainbow Pitta (*Pitta iris*), Emerald Dove (*Chalcophaps indica*), Rose-crowned Fruit-Dove (*Ptilinopus regina*) or Little Shrike-thrush (*Colluricincla megarhyncha*).

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Australites from four localities in the Eastern Goldfields, Western Australia

W H Cleverly

Western Australian School of Mines
PO Box 597, Kalgoorlie WA 6430

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Abstract

Four samples of australites from the Eastern Goldfields of Western Australia containing 244-616 specimens each have been examined. Specific gravity frequencies are those of the "normal australite" chemical type. Most differences in morphology between the samples can be understood in terms of distance from the salt lakes and degrees of exposure to weathering and erosion. Mean weights of whole specimens in the four locality samples increase irregularly from 1.62 g in a sample with the number of cores to lens-forms in the ratio 0.18 to 3.67 g in a sample with ratio 0.89. It is concluded tentatively that there was little initial variation in the morphology of the australites from place to place in the Eastern Goldfields except in those features such as percentages of cores and lens-forms, which are size-dependent.

Introduction

Australites (Australian tektites) have been found abundantly at numerous localities in the southern half of Western Australia, but collections contain few representative locality samples. A thoroughly representative sample requires the recovery of all possible australites from the area, including the smallest ones and fragments. If the sample is to be classified in some system which has many categories, it also needs to be sufficiently numerous for the less common types to be correctly represented. The four samples examined in this study contain only 244-616 specimens each. However, all samples are from the private collections of Mr and Mrs R G Tillotson and Mr and Mrs L D Tillotson of Kalgoorlie, and thus have been gathered by unusually thorough and acute observers. The large size of the Tillotson collections (c 11 000 australites) is an indication of that acuity of observation. A few australites from the four localities held in other collections were also examined but are not included in the statistics of the samples.

Samples 1-4 were found in the Eastern Goldfields within the semi-arid interior of Western Australia (Fig. 1). Mean rainfall is less than 250 mm/a. Drainage is internal to salt lakes which rapidly evaporate to dryness, their usual condition. Australites are found in this region on the surface of the ground or partly embedded in surficial materials. Australites are moved towards the salt lakes by soil creep processes and rain wash. They are thus found especially on the low-lying approaches to the lakes, in the beds of ephemeral rain-wash streams, on the flat alluvial fans at the lake edges, and elsewhere along the margins of the lakes.

Each of the Samples 1-4 was classified morphologically. Detailed statements are not presented, but extracts from the classifications are shown in Table 1, columns 1-4 respectively. The classification and extracts follow the system and methods of Cleverly (1986).

The Eastern Goldfields are central to a large area comprising the southern half of Western Australia and immediately adjacent part of South Australia in which australites belong to the "normal" chemical type of Chapman (1971, Fig. 2). The frequency diagram of specific gravity for the normal type has a single mode in the 2.44-2.46 interval and no values >2.47 (Chapman 1971). Analyses of australites from the "normal australite" region with specific gravity and refractive index data are given by Mason (1979, Table 1. analyses 1-13).

Location and description of Samples 1-4

Sample 1 Goongarrie Mining Centre is 82 km NNW of Kalgoorlie (Fig. 1). The nearby Lake Goongarrie is usually dry and wind-swept, there being no surrounding high ground to afford protection. The australite sample of 379 specimens was gathered from the gently sloping western

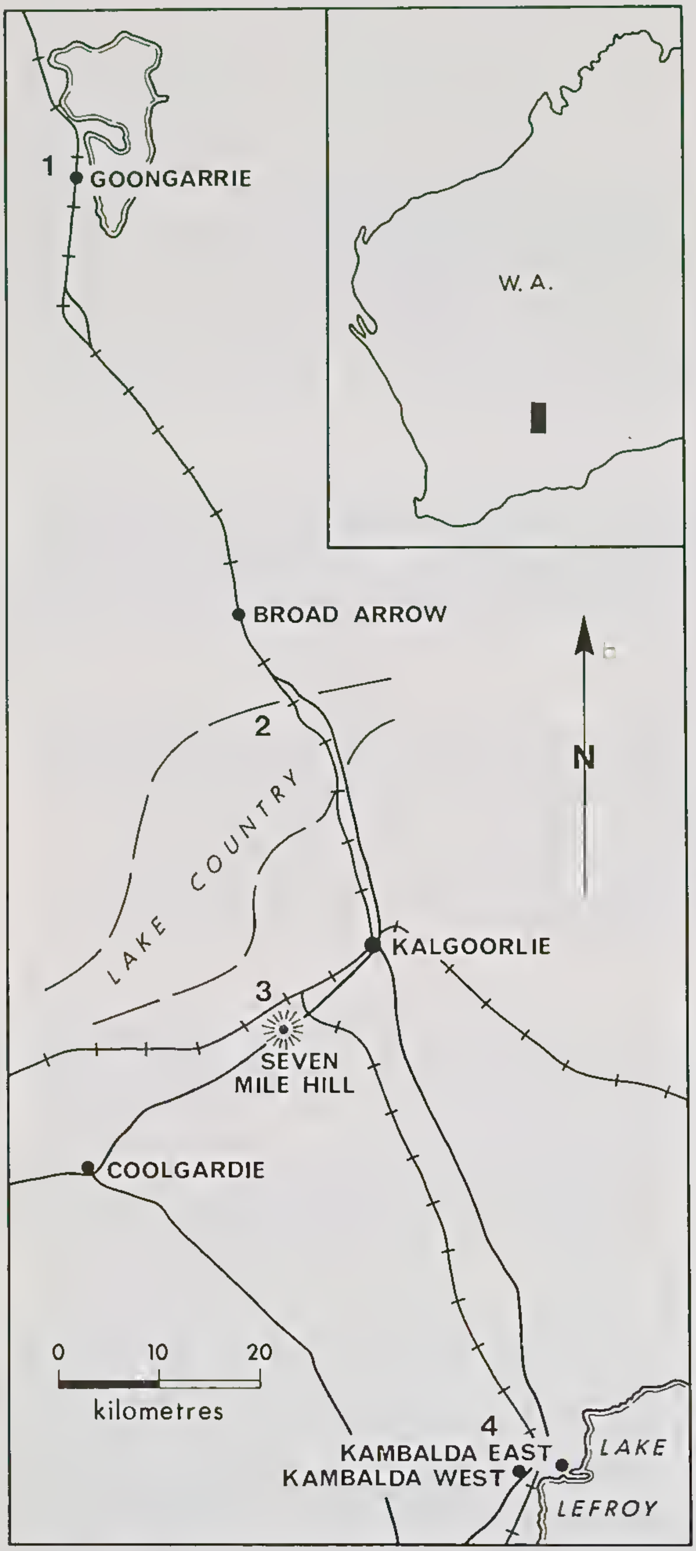

Figure 1 Part of the Eastern Goldfields, Western Australia, showing find sites of australite samples 1-4. Inset: Western Australia showing location of map area.

approaches to the southern half of the lake and the adjoining western portion of the lake.

Most australites from this area are severely abraded (Fig. 5A), though not to the extreme pebble shapes shown

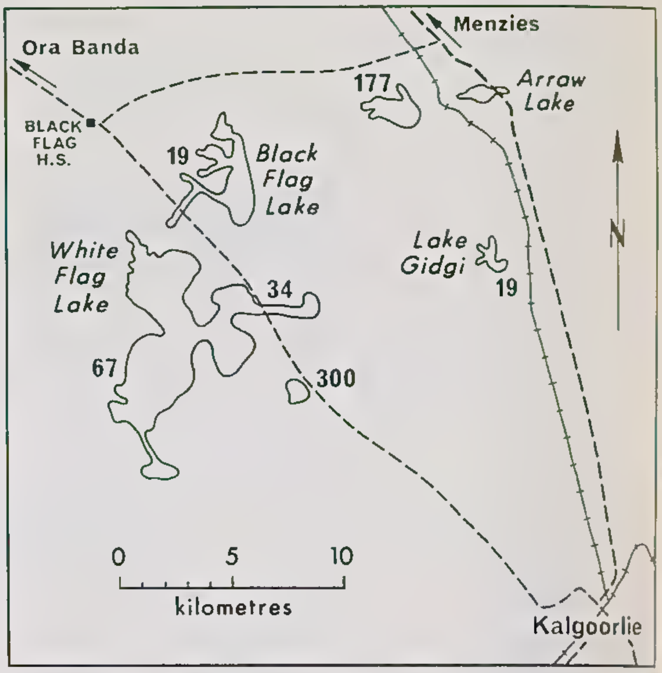

Figure 2 Country north-west of Kalgoorlie, Western Australia, showing localities and numbers of australites constituting the sample from the lake country. Only pertinent lakes are shown.

by those from Lake Wilson, South Australia, where australites now show no evidence of flanges or flow ridges (Chapman 1964).

Cores in the Goongarrie sample have well rounded elevational profiles rather than defined rims (Fig. 5B). Worn flow ridges are sometimes recognisable (Fig. 5C), but well preserved flow ridges or other indications of flight orientation are unusual (Fig. 5D). Thus, although a lens-form may be recognised by its cross section, its flight orientation is generally indeterminate. Australites with V-grooves (Fig. 5E) or other evidence of chemical etching are also unusual.

The sample contains only 10 shape types (Table 1, item 1). With the exception of a few stout aberrant forms, the identifiable fraction consists of lens-forms and cores (items 15 and 17), the ultimate identifiable survivors of smaller and larger primary bodies respectively. Flanged forms, indicators and fragile forms have been converted to more stable end shapes or rendered unrecognisable in the severely abrasive conditions near the margin of the lake. The abraded state of this sample is reflected also in the unusually low 28.5% of identifiable specimens (Table 1, items 2, 3 and 6). Abrasion—rather than derivation from primarily round bodies—is the likely reason for the exceptionally high 85.4% of round forms (item 7). In contrast, the mean percentage and standard deviation for round forms in five other samples from the Eastern Goldfields (Cleverly 1986, 1988a, samples 2-4 of this paper) are 64.4±3.2%.

The specific gravities of 333 specimens from Goongarrie in the Tillotson collections were determined by Chapman (1971, Fig. 4(d)). The figure illustrates typical "normal australites and normal philippinites" in Chapman's chemical classification.

Table 1

Comparison between australite samples from **1** Goongarrie **2** Lake country NW of Kalgoorlie **3** Seven Mile Hill **4** Vicinity of Kambalda

		1	2	3	4
1	Number of shape types in sample	10	15	21	18
2	Complete forms or essentially so %	18.2	34.4	39.1	50.4
3	Incomplete but classifiable %	10.3	15.9	14.7	11.5
4	Unclassifiable, largely abraded or fragments %	70.7	49.2	45.8	38.1
5	Flakes and flaked cores %	0.8	0.5	0.3	-
6	Total classifiable %	28.5	50.3	53.8	61.9
7	Round forms %	85.4	68.5	64.5	63.3
8	Broad oval forms %	1.0	7.9	9.7	9.5
9	Narrow oval forms %	3.9	7.2	6.5	10.2
10	Boat forms %	4.8	4.6	5.2	5.4
11	Dumbbell forms %	3.9	7.2	8.9	7.5
12	Teardrop forms %	1.0	4.6	5.2	4.1
13	Flanged, disc and plate, bowl and canoe forms %	-	-	7.1	1.4
14	Indicators I %	-	0.7	3.9	2.7
15	Lens-forms %	64.1	75.6	74.9	49.7
16	Indicators II %	-	0.7	0.6	2.0
17	Cores %	35.9	23.0	13.5	44.2
18	Total fragile forms and indicators %	-	1.4	11.6	6.1
19	Cores/lens forms	0.56	0.30	0.18	0.89
20	Number of essentially complete forms	69	212	117	123
21	Mean weight of above (g)	1.93	1.71	1.62	3.67
22	Total number of specimens in sample	379	616	299	244
23	Mean weight of all specimens (g)	1.37	1.21	1.24	2.53

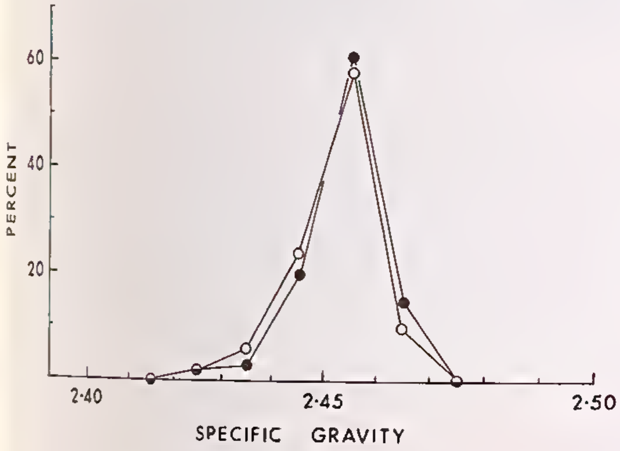

Figure 3 Frequency diagrams of specific gravity for australites. Open circle: sample of 50 australites from lake country north-west of Kalgoorlie. Filled circles: sample of 59 australites from Gindalbie and Broad Arrow from Chapman *et al* (1964, Fig. 3).

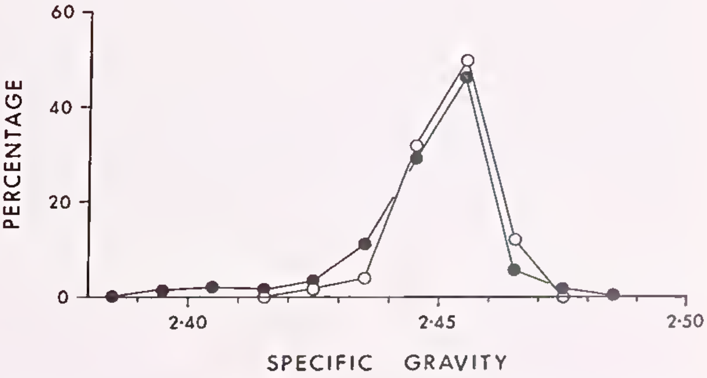

Figure 4 Frequency diagrams of specific gravity for australites. Open circles: sample of 50 australites from the vicinity of Kambalda. Filled circles: sample of 268 australites from the Kalgoorlie area from Chapman *et al.* (1964, Fig. 3).

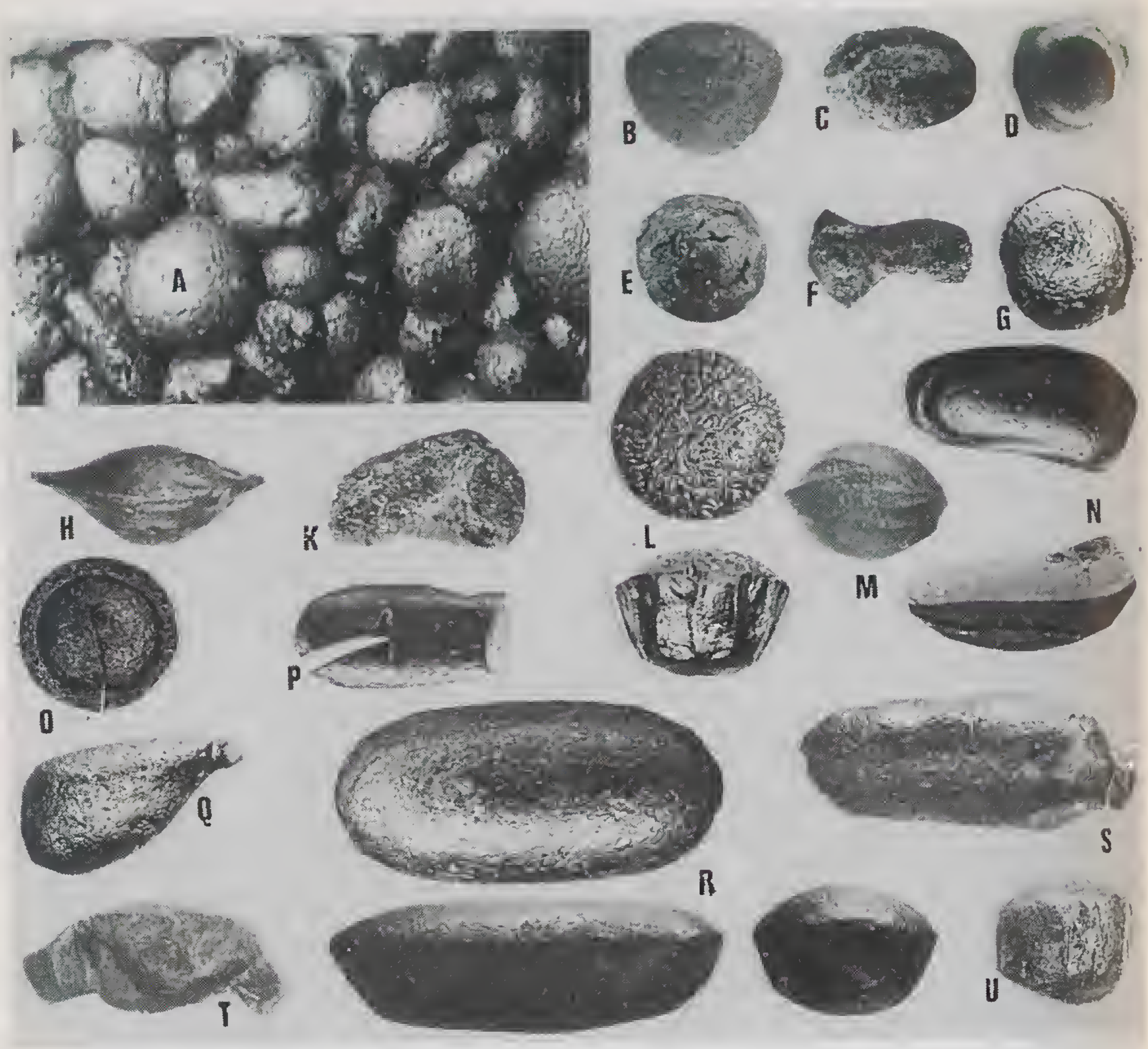

Figure 5 Australites from the Eastern Goldfields, Western Australia, natural size except where otherwise stated. In side or end views, direction of flight is towards bottom of page. A Typical australites from Goongarrie showing abraded forms. B Round core, side view showing lack of defined rim, Goongarrie, x 1.2. C Severely abraded, square-ended aberrant form, anterior surface showing faint remnants of longitudinal flow ridges, Goongarrie, x 1.2. D Lens with remnants of butt of flange, anterior surface showing flow ridge unusually well preserved for Goongarrie area, x 1.2. E Round core, anterior surface with etched V-grooves, Goongarrie, x 1.2. F Fragment of elongated indicator II with remnant of stress shell on one end, Goongarrie. G Round indicator I, posterior surface, lake country NW of Kalgoorlie. H Broad oval canoe, side view, Seven Mile Hill area, x 1.5. K Vesicular fragment, D2.409, Seven Mile Hill area, x 2. L Round core, posterior surface above with etch pattern, side view below with rectangular flake scars, Seven Mile Hill area. M Seed type aberrant form, anterior surface with flow ridges, Seven Mile Hill area, x 1.5. N Elongate fragment, anterior surface above with flow ridges, side view below with turned up flange in middle of front face, Seven Mile Hill area, x 1.5. O Flanged broad oval, posterior surface, elongation 1.04, Kambalda area. P Fragment of elongated lens-form with pronounced sawcut, Kambalda area, x 1.5. Q Teardrop-indicator II, side view, Kambalda area. R Boat-core, posterior surface above, side view below, end view below right, Kambalda area. S Boat-indicator II, posterior view. Spalling has occurred from this surface. Kambalda area. T Narrow oval indicator II, side view showing small remnants of stress shell at each end, Kambalda area, x 1.5. U Small round core, side view showing numerous narrow parallel flake scars, Kambalda area.

mple 2 An area centred 20 km NW of Kalgoorlie ains several tens of closely crowded, usually dry lake ns and clay pans with intervening gypseous dunes. local name for such terrain is "lake country" (Fig. 1). 616 australites in the sample are from 6 parcels, each result of searching dry basins and their approaches 2). Some of the smaller lakes or parts of lakes have graphic protection. A few australites of the less ist types have therefore survived (Fig. 5G).

he morphology of Sample 2 from the lake country ble 1, col 2), with one notable exception, is rather ilar to that of the sample from the extensive lake em on Hampton Hill Station (Cleverly 1986). Thus, the sifiable percentage (item 6) is a 50.3% (Hampton Hill ion 49.8%) and the percentage of round forms (item 7) 8.5% (cf. 66%). The exception is in items 15 and 18, ing a cores/lens-forms ratio of 0.30 in contrast with 4 for the Hampton Hill sample. Cores range up to large e, but lens-forms are derived from flanged forms of ited thickness (Cleverly 1988b). A low cores/lens-ns ratio suggests that the mean weight of whole cimens will also be low. Thus, for Sample 2, the mean ight is 1.71 g (item 21), but for Hampton Hill Station it .08 g (Cleverly 1986). Table 1, items 19 and 21 show the egular increase of mean weight from 1.62 g at the ratio 3 to 3.67 g at ratio 0.89. Although there are several own exceptions to this general trend in samples from ewhere, this is because the ratio depends, *inter alia*, on quality of the sample. For example, a carelessly lected sample tends to contain an unduly high proportion of the larger (core type) specimens and thus to have a sleadingly high cores/lens-forms ratio and high mean ight.

A frequency diagram of specific gravity for 50 australs from Sample 2 (Fig. 3) is unimodal with 41 of the ues in the 2.44-2.46 range and no values exceeding 2.47. e diagram matches closely the one for a sample of 59 stralites from Broad Arrow and Gindalbie (Chapman *et* 1964, Fig. 3), a typical "normal australite" diagram.

Sample 3 Seven Mile Hill is 12 km SW of Kalgoorlie ride Great Eastern Highway (Fig. 1). The sample of 299 stralites was gathered from 2-3 km SE of the hill below e low lateritic plateau known locally as Afghan Rocks, which there is a group of gnamma holes (Honman 14, Pl. III). Drainage is to the eastern end of a belt of ake country", distinctly separate from that of Sample 2.

Much of Sample 3 was collected further from the lakes an the other samples. Sample 3 contains a number of nall and fragile forms, and thus has a rather high mber of shape types for a sample of this size (Table 1, l 3). Details of several of the small specimens, with an count of the role of folding in their development, have en given by Cleverly (1979). The fragile forms include a oken pineseed described by Cleverly (1982).

Afghan Rocks gnamma holes was an aboriginal occupaon site which has been searched for the presence of istralite artifacts (Cleverly and Cleverly 1985). Flakes of nalcedony and other fine-grained siliceous materials are resent on the gentle rise overlooking the gnamma holes, ut no australite flakes were found. The sample in the llotson collections from the breakaways and ground below the plateau contains a single australite flake. Destructive use of australites by aborigines was evidently minimal in this area. The likely reasons are a lack of large australites (only two in the sample weigh more than 10 g each), and/or the ready availability of a variety of usable, fine-grained siliceous rocks.

A frequency diagram of specific gravity for 275 australites from Seven Mile Hill in the Tillotson collections (Chapman 1971, Fig. 4(d)) is part of a figure illustrating "normal australites and normal philippinites" in Chapman's chemical classification.

Sample 4 The first Kambalda township, on an angular promontory jutting into Lake Lefroy 55 km SSE of Kalgoorlie, was dependent on gold mining for its existence. Australites were well known in the principal alluvial patch at the lake edge south of the township, and were highly regarded by local propectors as indicators of good gold values (G Cleverly *pers comm*). This belief was once held in other goldfields also (Baker 1959). The modern Kambalda East, a more extensive town in the same general area as the first town, is concerned with nickel and gold mining. Kambalda West is a dormitory town centred 4 km WSW of Kambalda East (Fig. 1).

The australite sample was gathered from two general areas:

(a) The low-lying ground extending from Kambalda West down to Lake Lefroy and along the margin of the lake (106 specimens).

(b) About 6 km N of Kambalda East in the bed of a large creek which flows SE into an angular embayment of the lake (75 specimens); also from the alluvial fan and lake in that vicinity (63 specimens).

Samples of 25 specimens from each of areas (a) and (b) have mean specific gravity and standard deviation 2.453±0.006 and 2.450±0.008 respectively. They have been accepted as parts of the same population. A frequency diagram of specific gravity for the combined samples (Fig. 4) is unimodal with 82% of the values between 2.44 and 2.46, and no values exceeding 2.47. The diagram matches closely the one for 268 specimens from the Kalgoorlie area (Chapman *et al* 1964, Fig. 3), a typical "normal australite" diagram.

Part of Sample 4 is from the flats south of Kambalda West, which are vegetated and have very little slope. The other part is from an area north of Kambalda East, where erosive forces are severe. It was possible to unite the two parts of the sample for a study of specific gravity, but their morphology (Table 1, col 4) would preferably have been considered as two separate units if specimen numbers had not been so small. As examples, the 50.4% of essentially complete australites (item 2) is made up of 57.5% for the western part of the sample and only 44.9% for the northern part: the 61.9% classifiable specimens (item 6) consists of 66.9% and 57.9% for the respective parts: the mean weight of 3.67 g for whole specimens (item 21) comprises 4.36 g for the western and 3.00 g for the northern parts of the sample. All of these differences are consistent with the greatly different environments of the western and northern parts of the sample area.

Discussion and conclusions

The four australite samples were collected by the same people within the one geographic and climatic region, and all are of the same chemical type. It is possible that the morphology of the australite shower varied little from place to place in the Eastern Goldfields, because the considerable differences now existing between samples may be largely understood by differences in the intensity of the weathering and erosion processes to which they have been subjected since arrival on the earth's surface. In particular, the degree of exposure to the open, salt lake situation, where erosion processes are severe, is a major factor.

A possible exception to uniformity in the shower was a difference in the sizes of the primary bodies from place to place. The development of flanged forms, and hence of lens-forms (amongst others), is limited to primary bodies of thickness less than c 40 mm (Cleverly 1988b). Because cores formed aerodynamically do not have that upper size limit, the original size differences may now show up in the cores/lens-forms ratio.

Factors other than weathering and erosion affect the nature of australite samples gathered elsewhere or by other people. In the well-vegetated south-west of Western Australia, australites are much more difficult to detect than on the bare ground and lake basins of the Eastern Goldfields. For example, 49 australites from the farm of F Davis east of Yealering, centred 32°37'S, 117°56'E, have mean weight 17.6 g and cores/lens-forms ratio 8.0. These figures contrast with the average values for the four samples discussed in this study, which are 1.59 g and 0.44. Careless or casual collection has much the same effect on the nature of the sample as obscuring vegetation. There are also places such as the Nullarbor Plain where human usage of australites has affected the nature of the samples, not only in the abundance of australite artifacts, but in the rarity or absence of the larger usable australites (Cleverly 1976, Table 1).

The study of further australite locality samples from outside the Eastern Goldfields is desirable before making firm decisions on these tentative conclusions.

Acknowledgements I thank Mr and Mrs R G Tillotson and Mr and Mrs L D Tillotson for the loan of australites. Figures 1-4 were drafted by Ms J M Wearne. My photographs used in Figure 5 were processed by Mr M K Quartermaine.

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JOURNAL OF THE ROYAL SOCIETY OF WESTERN AUSTRALIA

CONTENTS VOLUME 71

PART 1 (Published 16 March 1989)

	Page
Regeneration of *Acacia* and *Kennedia* from soil stored seed following an autumn fire in jarrah (*Eucalyptus marginata*) forest **W L McCaw**	1
Calc-alkaline lamprophyres from the Pilbara Block, Western Australia **N M S Rock & M E Barley**	7
Widespread regeneration failure of *Persoonia elliptica* (Proteaceae) in the northern jarrah forest of Western Australia **I Abbott & P Van Heurck**	15

PARTS 2 and 3 (Published 25 May 1989)

The Quindalup Dunes: the regional system, physical framework and vegetation habitats **V Semeniuk, I D Cresswell & P A S Wurm**	23
A field guide to the dung beetles (Scarabaeidae: Scarabaeinae and Aphodiinae) common in pastures of South-western Australia **T J Ridsdill-Smith, G P Hall & T A Weir**	49
The early evolution of the plant life of South-western Australia **J S Beard**	59
Spatial variation in fish communities in two South-western Australian river systems **B J Pusey, A W Storey, P M Davies & D H D Edward**	69
A simple model to forecast wheat yield in Western Australia **D J Stephens, T J Lyons & M H Lamond**	77

PART 4 (Published 26 October 1989)

BANKSIA WOODLANDS SYMPOSIUM

Page

Preface **J S Pate** 83

Jennifer Mary Arnold, BSc, BA, MSc, PhD—An appreciation **E P Hodgkin** 83

Definition and location of the *Banksia* woodlands **J S Beard** 85

Bassendean and Spearwood dunes: their geomorphology, stratigraphy and soils as a basis for habitats of *Banksia* woodlands **V Semeniuk & D K Glassford** 87

Floristics of the *Banksia* woodlands **J Dodd & E A Griffin** 89

Water relations of *Banksia* woodlands **J Dodd & E M Heddle** 91

Fire in the *Banksia* woodlands of the Swan Coastal Plain **A J M Hopkins & E A Griffin** 93

Terrestrial invertebrate fauna **J D Majer** 95

Vertebrate fauna of *Banksia* woodlands **R A How & J Dell** 97

Biotic and abiotic interactions in *Banksia* woodlands **B Lamont** 99

Management of groundwater resources for protection of native vegetation **J Kite & K Webster** 101

Urban development **M D Poole** 103

Impact of horticulture on *Banksia* woodlands **I R McPharlin & B A Stynes** 105

Forestry and *Banksia* woodlands on the Swan Coastal Plain **E R Hopkins** 107

Mineral resources and mining of the Spearwood and Bassendean dune systems **J R Gozzard & M J Mouritz** 109

Banksia woodland weeds **G J Keighery** 111

Page

Diseases of *Banksia* woodlands on the Bassendean and Spearwood dune systems **B L Shearer & T C Hill** 113

Conservation status of *Banksia* woodlands on the Swan Coastal Plain **S D Hopper & A H Burbidge** 115

Banksia woodlands: Summary and conclusions **A A Burbidge** 117

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JOURNAL OF THE ROYAL SOCIETY OF WESTERN AUSTRALIA

CONTENTS VOLUME 72

PARTS 1 and 2 (Published 21 February 1990)

Page

Fungal and bacterial diseases of plants in Western Australia
R G Shivas 1

PART 3 (Published 30 April 1990)

Mortality and growth of tree species under stress at Lake Toolibin in the Western Australian Wheatbelt **D T Bell & R H Froend** 63

Motor vehicle emission inventory for the Perth airshed **T J Lyons, R O Pitts, J A Blockley, J R Kenworthy & P W G Newman** 67

Stratification and disconformities in yellow sands of the Bassendean and Spearwood Dunes, Swan Coastal Plain, South-western Australia **D K Glassford & V Semeniuk** 75

PART 4 (Published 3 August 1990)

Natural products from Western Australian marine organisms
E L Ghisalberti & P R Jefferies 95

Wetlands of the Darling System, Southwestern Australia: a descriptive classification using vegetation pattern and form **C A Semeniuk, V Semeniuk, I D Cresswell & N G Marchant** 109

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Distribution of diatoms in the northern Kimberley region, Western Australia in relation to water chemistry

E R Tudor,[1] Dean W Blinn,[2] and David M Churchill[3]

[1] Beaconhills Christian College, PO Box 160, Pakenham 3810, Australia
[2] Department of Biological Sciences, Northern Arizona University,
Flagstaff, AZ 86011, USA
[3]Royal Botanic Gardens, Birdwood Avenue, South Yarra, Vic 3141, Australia

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Abstract

118 diatom taxa from 31 genera were identified from 18 sites in the mid-northern Kimberley region of Western Australia. 12 taxa (10% of the total) are recorded for the first time in Australia. Diatom taxa were clustered into groups using Euclidean distance metric analyses. 17 species (14% of the total) occur over a wide span of total dissolved solids (within the range of 30-42 000 mg/L), nitrate levels (0.4-7.8 mg/L) and pH regimes (5.3-8.4). 92 species (78%) are distributed in discontinuous groups at sites ranked along TDS gradients. *Navicula radiosa* and *N. pupula* were the most widespread.

Introduction

There have been relatively few surveys of diatoms from inland waters on the Australian continent (Thomas 1983). Those regions which have been examined for diatoms include the coastal regions of Victoria, New South Wales, and Queensland (Foged 1978), a variety of water bodies in Tasmania, Victoria, and South Australia (Tudor 1973), and the Magela Creek system (Brady 1983) and Alligator River Region (Thomas 1983) of the Northern Territory. John (1983b) prepared an extensive survey on the diatom flora of the Swan River Estuary near Perth, Western Australia, and has conducted a number of detailed studies with light and electron microscopy on diatom species collected from the Swan and Canning Rivers, and nearby regions around Perth (John 1980, 1981a, 1981b, 1981c, 1982a, 1982b, 1983a, 1983b, 1986).

To date there have been no published surveys of diatoms in the Kimberley region in the northwestern part of Western Australia. John (1982b), however, did report on the morphological variation of *Cymbella sumatrensis* in collections from Lake Argyle, Western Australia.

The Kimberley region represents a relatively isolated region on the Australian continent and may provide a distinct diatom flora from that previously reported in Australia. We present a survey of the diatoms found in several creeks and large rivers in the mid-northern Kimberley region. These systems contain waters with a wide range of total dissolved solids (TDS) and dissolved nutrients.

Study Site and Methods

The study area was located on the Gardner Plateau (600 m) within 150 km of Drysdale River National Park in the Kimberley region of Western Australia (Fig. 1). The Kimberley region is considered to have a dry, monsoonal climate and to undergo extreme seasonal variability in annual rainfall with the wet season occurring during December to March (Forbes and Kenneally 1986). The annual mean precipitation for the northern Kimberley is 800-1 000 mm. This study was conducted at the end of the dry season during August 1981 and the creeks and rivers contained little water. Many of the smaller rivers and creeks were merely isolated water holes whilst the larger rivers, although still flowing, had water levels well below the wet season peak.

Benthic diatoms and water samples were collected by E R Tudor from the 18 locations listed in Fig. 1. Water temperature and pH were measured at each sampling site. Nitrate-nitrogen was measured by the cadmium reduction procedure, ortho-phosphate by the molybdate method, and total dissolved solids (TDS) by evaporating a known volume of filtered water sample to dryness at 100°C and weighing the residue (APHA 1976).

Diatom frustules were cleared of organic matter in concentrated H_2SO_4. Two 1 mL aliquots of the cleaned diatom material from each sample were dried and mounted in Hyrax on cleaned glass slides. At least 500 frustules were counted from each sample to determine the relative frequency of each taxon. The permanent diatom slides used in this study are housed at Northern Arizona University, Flagstaff, AZ, USA, and the original samples are held by E R Tudor.

The diatom taxa (identified by DWB) were clustered (by DMC) from a computer database (Paradox) used to generate an analog table of presence-absence data [1 or 0 for each species and each site]. The report facility of the data base was then used for the two-way sorting of Table I which was printed using Word5 with Postscript. The clustering process, based on presence-absence data (not relative percentage frequency), gave equal weight to each species recorded from each site. From the range of linkages tested (using the program SYSTAT), the Euclidean distance metric analyses with complete linkage to furthest neighbour was selected for final grouping. Green, Carmone, & Smith (1989) discuss this linkage in a recent review of clustering methods.

Nineteen groups of species with the most similar range of occurrence were arranged in a non-hierarchical sequence of groups to show the nature of the gradient (whether continuous or discontinuous) when the sites were arranged in columns from the least to the highest concentration of TDS (Table 1).

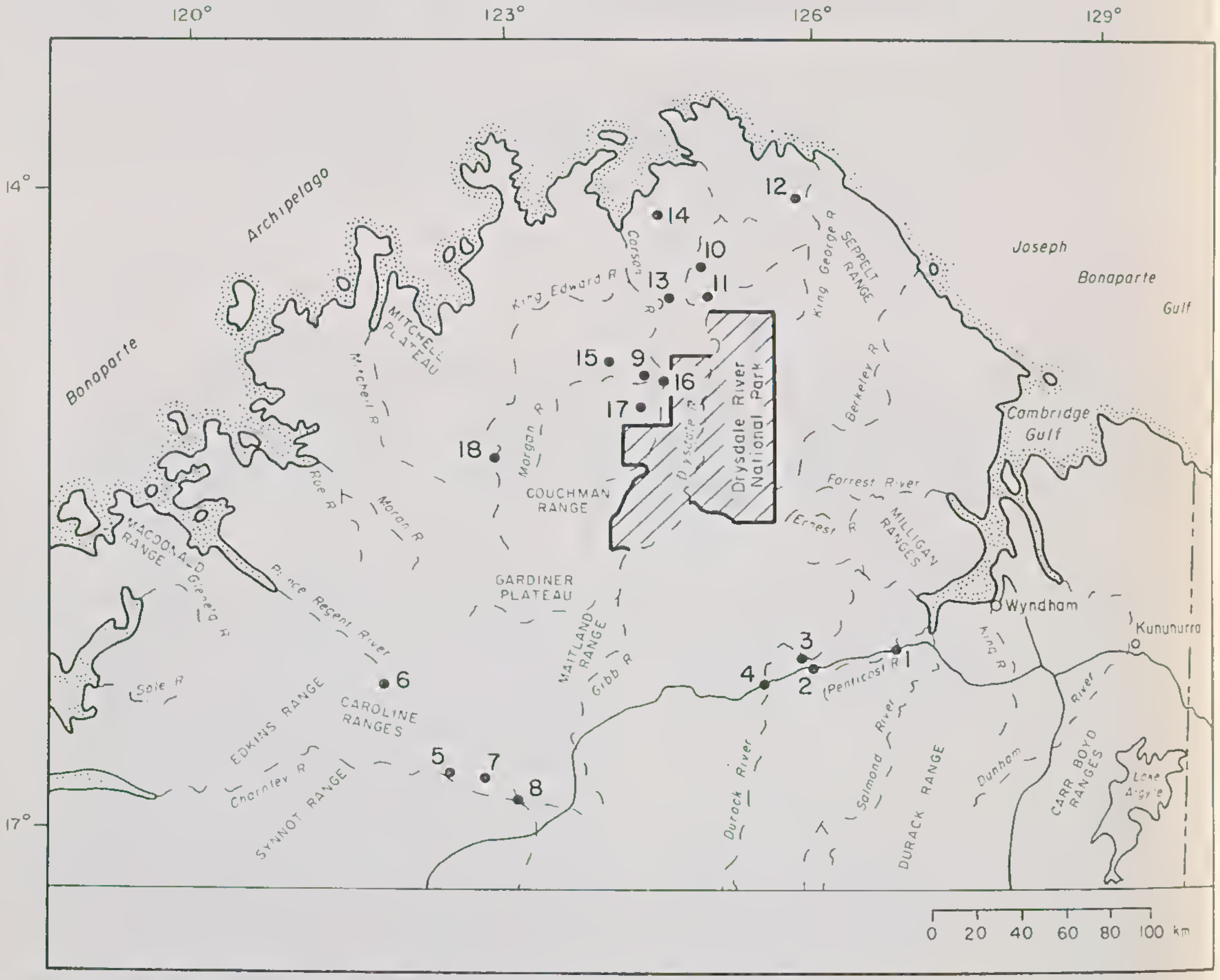

Figure 1 Map indicating the 18 collection sites in the North Kimberley region, Western Australia. Sites 1-18 indicated. 1. Pentecost River; rocks in residual pools. 2. Residual pool in Palmer Creek with dense plant growth; used by livestock. 3. Residual pool close to Durack River; abundant water lilies. 4. Residual pool in Durack River. 5. Deep residual pool at Magpie Springs; dense growth of filamentous algae. 6. Creek between Mount Jameson and Mount Agnes. 7. Tributary of Drysdale River; pool with slow flow and dense aquatic plant growth. 8. Hann River; water flowing; sandy with dense aquatic plant growth; used by livestock. 9. Morgan River; sandy substrate; used by livestock. 10. Tributary of Drysdale River; small residual pool; rocky substrate; abundant filamentous algae; used by livestock. 11. Redidual pool in dry creek bed near Drysdale River; *Pandanas* palms growing close to creek; used by livestock. 12. Residual pool in tributary of King George River; abundant growth of water lily; used by livestock. 13. Carson River; slow flowing water through shallow pools. 14. Residual pool in creek south of Pago Mission; sandy and rocky substrate. 15. Residual pool in creek between Theda and Old Theda Station. 16. Residual pool in Carson River at crossing close to Old Theda Station. 17. McDonald Creek; residual pool; rocky substrate. 18. King Edward River; rocky substrate; water lily in pools and *Pandanas* palms adjacent to river.

Table 1

Diatom species from northern Kimberley region, Western Australia. Species grouped by Euclidean distance metric with complete linkage to furthest neighbours.

			New Aust. Record	Locality Number (Sites ranked, from lowest to highest Total Dissolved Solids)																	
				9	17	7	3	2	8	15	16	18	4	6	5	12	14	11	13	10	1
SITE CHARACTERISTICS																					
TDS	Total Dissolved Solids	mg/L		30	40	40	80	90	100	110	110	170	200	210	250	250	370	370	460	660	42000
NO_3-N	Nitrogen	mg/L		<0.4	<0.4	<0.4	1.3	3.3	<0.4	2.4	1.3	<0.4	1.3	1.4	<0.4	<0.4	<0.4	1.3	0.4	7.8	1.9
O-PO_4	Phosphate	mg/L		0.03	0.11	0.09	0.04	0.16	0.06	0.94	0.18	0.42	0.05	0.03	0.06	0.07	0.03	0.02	0.05	0.20	0.22
pH	Acidity			7.3	6.5	5.3	6.6	6.4	6.7	7.5	7.5	7.2	6.7	7.4	6.9	5.9	6.2	7.2	8.4	7.4	7.6
L/Stn	Livestock use. Near old station/mission			L				L	L	Stn	Stn					L	M	L		L	
DIATOM TAXA (percentage frequency; * < 1%)																					
Group 1																					
Nitzschia palea (Kutz.) W. Sm.					7	4.2	6.2	5.6	8	5	4.5	9.6	2.4	5.8	64.2	23	*	*	*	8	
Gomphonema gracile Ehr. Emend. V.H.					*	*	3.8	6.2	2	1.6	*	1.6	4.8			*		6.2	24	2	
Achnanthes minutissima Kutz.					11.4	13	27.2	*		8.6	9		39.6	4		10	*	16	27	1.8	
Achnanthes microcephala (Kutz.) Grun.					*	1.8	*	*		*	*		*	*		1.2	*	*	*	6	
Navicula cuspidata (Kutz.) Kutz.				1.8		*	1.8	1.6		*	*		*	*			*	4	3	*	
Nitzschia kuetzingiana Cl.				*	*			5.8	*	1.6			*		*	8	*		*	4	
Stauroneis phoenicenteron (Nitz.) Ehr.				*				7.4	*		*	1.8	1.8	*		*	1.2	*		*	
Navicula radiosa Kutz.				48	11.6		10.8		55	10	4.5	13	12.4	65.8	3	1.8		30.2	4.2	24	*
Navicula pupula Kutz.				*			11.8	10.2	*	1.6	*		5	*		*		1.8		*	*
Group 2																					
Navicula cryptocephala Kutz.				1.8	27.6				1.8	11.6	9	*			*			18.2		25.6	
Synedra ulna (Nitz.) Ehr.				2	3.7		*		*	*	*	4.8		2	*					*	
Cymbella sumatrensis Hust.				*	*		*					*			*			*	*	*	
Achnanthes exigua Grun.				*					*	*	*			*				*		*	
Cyclotella stelligera Cl. & Grun.				*		*	1.6			*	4.5			*	*		*			2	
Neidium affine (Ehr.) Pfltz.							*	*	*	5	*			*	*					*	
Pinnularia braunii var. amphicephala (A.Mayer ex Hust.) Patr.				*		4.6			*		*	4.8	*	2.4		2.6	*	*	2		
Cymbella cymbiformis var. *nonpunctata* Font.			+	4.2	8					*	*	49.6		*				4.2	6.2	6.2	
Group 3																					
Hantzschia amphioxys (Nitz.) Ehr.				*				*				*	7.8					*	*	*	
Gomphonema parvulum (Kutz.) Kutz.								17.2	7.8			*	6.2						4.8		
Melosira granulata (Ehr.) Ralfs				*			12.2			*	4.5	*	2.4					*	16.4		
Group 4																					
Cymbella minuta var. *silesiaca* (Bleisch ex Rabh.)				*			4.4			*		*			*	*				*	
Eunotia flexuosa Brab. ex Kutz.							*	*				*				4.2					
Eunotia camelus Ehr.				7.6		25.8	*	13.8				1.4	2.2			3					
Surirella linearis W. Sm.				*			*					*	*							**	
Stenopterobia intermedia Lewis				4.8	1.2		*		9.2				*								
Surirella tenera Greg.				*							*			*							
Nitzschia fonticola Grun.				4				*		18.3											
Nitzschia filiformis W. Sm.				*																	

Table 1—*continued*

Diatom species from northern Kimberley region, Western Australia. Species grouped by Euclidean distance metric with complete linkage to furthest neighbours.

	New Aust. Record	Locality Number (Sites ranked, from lowest to highest Total Dissolved Solids)																	
		9	17	7	3	2	8	15	16	18	4	6	5	12	14	11	13	10	1
Group 5																			
Surirella linearis var. *constricta* Grun.				2															
Eunotia formica Ehr.				*															
Nitzschia gracilis Hantz.			60	2.8								*							
Navicula subrhynchocephala Hust.				2								*							
Group 6																			
Melosira italica (Ehr.) Kutz.		6.4			*														
Frustulia rhomboides (Ehr.) DeT.					.1														
Nitzschia lorensiana var. *subtilis* Grun.					*														
Stenopterobia intermedia var. *subacuta* Fricke					*														
Group 7																			
Navicula subatomoides Hust.							*							*					
Opephora martyi Herlb							*												
Navicula pupula var. *rectangularis* (Greg.) Grun.							*												
Navicula mutica var. *cohnii* (Hilse) Grun.							*												
Eunotia tenella (Grun.) Cl.				14.2			*												
Eunotia incisa W. Sm. *ex* Greg.	+			2.4			*												
Navicula radiosa var. *parva* Wallace	+						2.4		*	6									*
Group 8																			
Synedra radians Kutz.	+							1.6	*								*	*	
Surirella robusta Ehr.								*											
Nitzschia vexans Grun. in V.H.	+							3.2											
Mastogloia elliptica var. *dansei* (Thwaites) Cl.								3.2											
Epithemia turgida (Ehr.) Kutz.								*											
Epithemia adnata (Kutz.) Breb.								8.3											
Amphora ovalis var. *affinis* (Kutz.) V.H. ex Det.								1.6	*										
Group 9																			
Gomphonema subclavatum var. *commutatum* (Grun) A. Mayer	+									*									
Neidium gracile Hust.										1.2									
Nitzschia vermicularis (Kutz.) Grun.					*					*									
Group 10																			
Eunotia pectinalis var *undulata* (Ralfs.) Rabh..				10	*	*				*		*							
Pinnularia biceps Greg.					2	*						*	*						
Cymbella bengalensis Grun.		*										*							
Navicula muticoides Hust.												*							
Hantzschia virgata (Roper) Grun.												*							
Rhopalodia gibba var. *ventricosa* (Kutz.) H.& P. Perag.												*	*						
Rhopalodia gibba (Ehr.) O. Muell.												*	*						
Hantzschia amphioxys var. *capitata* O. Mull.							4.8					*							
Gyrosigma spencerii (Quek.) Griff. & Henfr.					*			*				*							
Anomoeoneis sphaerophora (Ehr.) Pfltz.								1.6				5.8						*	

Group 11																					
Cymbella turgida (Greg.) Cl.							*								*						
Cyclotella meneghiniana Kutz.															*						
Navicula pupula var. *capitata* Skv. & Meyer															2						
Nitzschia linearis W. Sm.															20.8						
Group 12																					
Eunotia pectinalis var. *minor* (Kutz.) Rabh..					6.8	10.8	*			1.6						1.6	1.2				
Stauroneis anceps f. *gracilis* Rabh.					*				*												
Navicula accomoda Hust.					*						*										
Caloneis bacillum (Grun.) Cl.																	*				
Stauroneis kriegeri Patr.																	*				
Frustulia rhomboides var. *saxonica* (Rabh.) DeT.																	6.2				
Navicula subtilissima Cl.					*												13.8				
Anomoeneis serians var. *brachysira* (Brab.ex Kutz.) Cl					*												70.8			*	
Group 13																					
Neidium affine var. *amphirhynchus* (Ehr.) Cl.													2								
Achnanthes exigua var. *heterovalva* Krasske													*								
Navicula halophila (Grun.) Cleve											*		*					*			
Hantzschia elongata (Hantz.) Grun.	+																	*			
Fragilaria construens var. *venter* (Ehr.) Grun.																		*			
Eunotia pectinalis (O.F. Mull?) Rabh..																		2			
Amphora ovalis (Kutz.) Kutz.																		*			
Caloneis ventricosa var. *minuta* (Grun.) Patr.	+												*					*			
Group 14																					
Eunotia naegelii Migula	+				74.4			19								33					
Pinnularia brevicostata Cl.								1.6								3.6					
Eunotia diodon Ehr.	+					7.8	*	7								1.8		3.8			
Stauroneis phoenicenteron var. *brannii* (Perog. & Herib) Voight	+						*	*										*			
Cymbella lanceolata (Ehr.) van Heurck							*											*			
Surirella biseriata Breb.																*		1.8			
Neidium iridis var. *amphigomphus* (Ehr.) A. Meyer								*										2			
Hantzschia amphioxys var. *vivax* (Hantz.) Grun.								*								*		*			
Stauroneis phoenicenteron f. *gracilis* (Ehr.) Hust.	+							*										*		*	
Pinnularia borealis Ehr.								*													
Neidium hustedtii Krasske								*													
Navicula mutica Kutz.							*	*													
Group 15																					
Eunotia curvata (Kutz.) Lagerst.																4.2			*		
Coconeis placentula var. *euglypta* (Ehr.) Cl.					3														*		
Anomoeneis serians (Breb. ex Kutz.) Cl.					*														*		
Amphora veneta Kutz.																			1.8		
Rhopalodia gibberula var. *vanheurckii* O. Muell.	+			2															3.2		
Group 16																					
Nitzschia intermedia Hantz.																				2	
Pinnularia mesolepta (Ehr.) W. Sm.							*													*	
Pinnularia obscura Krasske							*													*	
Rhopalodia gibberula (Ehr.) O. Muell.																				*	*
Group 17																					
Coconeis placentula var. *lineata* (Ehr.) V.H.											*				*				*		
Rhizosolenia eriensis Smith										*					*		*		*		*
Nitzschia punctata W. Sm.																			*		*
Entomoneis paludosa (W. Sm.) Reim.																			*		1.2
Amphora coffeiformis (Ag.) Kutz.																			*		19.6

Table 1—*continued*

Diatom species from northern Kimberley region, Western Australia. Species grouped by Euclidean distance metric with complete linkage to furthest neighbours.

	New Aust. Record	Locality Number (Sites ranked, from lowest to highest Total Dissolved Solids)																	
		9	17	7	3	2	8	15	16	18	4	6	5	12	14	11	13	10	1
Group 18																			
Nitzschia frustulum (Kutz.) Grun.					*			3.2	*										*
Thalassiosira lacustris (Grun.) Hasle																			*
Diploneis suborbicularis (Greg.) Cl.								*											1.2
Diploneis oblongella (Naeg. ex Kutz.)		*																	2.8
Nitzschia granulata Grun.																			2.8
Nitzschia sigma (Kutz.) W. Sm.																			3.2
Navicula heufleri var. *leptocephala* (Breb.ex Grum) Patr.	+																		5.8
Pleurosigma elongatum W. Sm.																			10.2
Amphora acutiuscula Kutz.																			15.6
Rhopalodia musculus (Kutz.) O. Muell.																			32.4
Group 19																			
Achnanthes lanceolata var. *dubia* Grun.					*				*		*								
Pinnularia abaujensis var. *subundulata* (A.Mayer ex Hust.) Patr.	+				*						*								

Results and Discussion

One hundred and eighteen diatom taxa from 31 genera were identified from 18 collection sites in the Kimberley region of Western Australia (Table 1). Water temperatures at the various sites ranged from 20°C to 30°C.

Pennate diatoms were the most common with taxa in the Naviculaceae and Nitzschiaceae making up 54% of the flora. The 12 taxa designated "+" in Table 1 have not been reported in other major regional diatom floras for continental Australia (Foged 1978, Brady 1983, John 1983b, Thomas 1983).

Navicula radiosa showed the widest distribution of all species collected in the region by occurring in 83% of the sites (mean relative abundance = 16.4%; s.e.± 4.7) at TDS values ranging from 30 to 42 000 mg/L, and pH values ranging from 5.9 to 8.4. *Navicula pupula* showed a similar distribution across a wide range of TDS and pH, but occurred in only 67% of the sites with an average relative abundance of <4.0.

The diatom floras are most clearly divided between those in freshwater sites with TDS <660 mg/L and those (Group 18) in the single highly saline sample with TDS of 42 000 mg/L. Few diatom species (mostly in groups 16 and 17) span this division within the TDS range from 460-42 000 mg/L.

Amphora acutiuscula, *A. coffeiformis*, *Entomoneis paludosa* and species of *Pleurosigma* are frequently associated with waters of high salinity in western USA and Canada (Czarnecki & Blinn 1977, 1978, Felix & Rushforth 1979, Tuchman & Blinn 1979, Czarnecki *et al.* 1981, Hammer *et al* 1983, Kaczmarska and Rushforth 1983). John (1983b) also found *Amphora coffeiformis* and a new variety of *Pleurosigma* (*P. elongatum* var. *grosse punctatum*) in habitats with high salinity in the Swan River estuary system near Perth, Western Australia.

Twenty species (Groups 1,2 and 3 in Table 1) are distributed over a wide range of dissolved solids from 30 to 660 mg/L. Most species however cluster into groups that are characteristic of intermediate ranges, with a few species within the group occurring discontinuously over a wide range of total dissolved solids.

Eunotia spp. tend to dominate the diatom floras (i.e. their relative frequency becomes greater than 40-50% of the diatom population) in the Kimberley sites when the water has a TDS less than 250 mg/L, a pH lower than 6.5 and nitrate lower than 3.3 mg/L. These findings are in agreement with Patrick and Reimer (1966) and Lowe (1974) for North American taxa and reports on the distribution of Eunotia in Australia (Foged 1978, Brady 1983, John 1983b, Thomas 1983).

Stenopterobia intermedia also frequently occurred in sites with low pH and low TDS, but the relative abundance was low (mean = 1.0%; s.e.± 0.5).

Water with the lowest TDS of 30 mg/L appears to be colonized by species with a wide ranging TDS tolerance rather than by species that are confined to low salinity. Those species which occur in the wide range of TDS also occur in the full range of nitrogen. The response to nitrogen is not correlated with TDS.

Species in groups 8 and 16 are found in water with higher (1.3-7.8 mg/L) nitrate levels. Species in groups 13 and 19 are characteristic of intermediate (>0.4-3.3 mg/L) nitrate levels and species in groups 5, 7, 11, 12 and 15 occur at lower (≤0.4 mg/L) nitrate levels.

The response to pH is less marked than that of nitrogen or TDS. Most species occur in waters with pH ranging widely from 5.2-7.3. Species in group 14 however occur mainly within the pH range 5.3-7.2. Those species in group 18 tend to occur in the pH range of 7.5-7.6. While those species in group 17 are characteristic of the highest pH range 7.6-8.4. Response to phosphate gradient is least apparent.

Table 1 provides a general impression of the ecology of the diatom flora from open water in the Kimberley region. About 20% of the species occur more or less continuously over a wide geographic range of freshwater containing 0-660 mg/L TDS. The remaining 80% of the species are found discontinuously at sites of similar TDS or nitrate levels. This suggests an opportunistic colonization of any site by 12 groups of diatoms that tend to be associated, if they occur at all.

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A new reference section for the Toolonga Calcilutite, Carnarvon Basin, Western Australia

David Lynch

Department of Geology, University of Western Australia, Nedlands, WA 6009

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Abstract

A detailed description of a reference section of the Toolonga Calcilutite within the type area, lower Murchison River valley, Western Australia is presented. An 18.5 m section of white *Inoceramus* calcarenite, sandy calcilutite and greenish calcilutite, comprising three easily identifiable lithostratigraphic units, 1.5 km west of the type section at latitude 27°35′54″S longitude 114°12′42″E was selected for study. The stratigraphic distribution of benthonic macrofauna, and 98 foraminiferal and 6 calcareous nannoplankton species is documented. Analysis of the faunal characteristics shows that the Toolonga Calcilutite was deposited in warm temperate, normal-salinity ocean waters of outer neritic to upper bathyal depths. The reference section encompasses the *Heterohelix papula* through *Globotruncana arca* planktonic foraminifera zones and the *Reinhardtites anthophorus* through *Aspidolithus parcus* calcareous nannoplankton zones indicating that the Toolonga Calcilutite is early Santonian to early Campanian in the type area.

Introduction

The Toolonga Calcilutite is the oldest Cretaceous chalk unit recorded in the onshore Carnarvon Basin and includes Santonian and Campanian strata. The formation is exposed in the Murchison River area, where it forms the upper unit of the Cretaceous succession (Clarke and Teichert 1948), and in the Hamelin Pool and Giralia Anticline areas where it is overlain by younger Cretaceous units (Hocking *et al.* 1987). An equivalent of the Toolonga Calcilutite, the Gingin Chalk, is recognized in the Perth Basin to the south of the study area (Feldtmann 1963, Playford *et al.* 1976, Rankin 1987).

This paper provides a detailed description of the lithostratigraphy, biostratigraphy and age of the Toolonga Calcilutite in the type area, lower Murchison River valley, and in particular records the distribution of foraminiferal faunas and age diagnostic calcareous nannoplankton encountered in closely spaced samples from a continuously exposed section of the Toolonga Calcilutite.

Clarke and Teichert (1948) named and described the 'Toolonga Chalk' and 'Second Gully Shale' in the Murchison House Station area. Later mapping by Johnstone *et al.* (1958) showed that the 'Second Gully Shale' could not be recognized consistently in the type area so both formations were placed together and named the Toolonga Calcilutite. The type section of the Toolonga Calcilutite was designated by Johnstone *et al.* (1958) based on their mapping of the southern Carnarvon Basin for West Australian Petroleum. The location of the type section is recorded on a series of aerial photographs used in the mapping and now held at the Geological Survey of Western Australia. The type section consists of a 26 m (85ft) thick succession of cream chalk and greenish calcilutite (Johnstone *et al.* 1958, Condon 1968 and Hocking *et al.* 1987). In the early literature there has been some confusion in the cited latitude and longitude positions of the type section and of nearby landmarks. This was clarified by Hocking *et al.* (1987) who positioned the type section location at latitude 27°36′00″S longitude 114°13′40″E, 2 km north northeast of Yalthoo Spring as shown here on Figures 1 and 2.

During field mapping and sampling for this study the area near Thirindine Point containing the type section was searched for suitable sections but slumping and weathering had obscured some of the outcrop here. A continuous section of the Toolonga Calcilutite was found approximately 1.5 km west of the type section locality. This reference section lies at latitude 27°35′54″S longitude 114°12′42″E, [Grid Reference 245441] as marked on the Gantheaume 1:100 000 topographic sheet (Edition 1) (Figure 1, 2) and represents the most complete section in the type area at the time of study. This study is based on the reference section.

Methods

Thirty eight samples were selected for grain-size distribution. Each sample was dried, weighed and wet-sieved through a 63 m sieve and the 63-2 000 μm fraction dried and weighed. To determine impurities, a composite sample of material from differing levels of the section, was placed in dilute hydrochloric acid (2 wt. %) to remove carbonate. Supernatant liquid was periodically replaced with fresh acid until effervescence ceased. The insoluble residue was filtered, washed to remove $CaCl_2$, dried and weighed. Analysis showed it to be a K, Na, Mg, Ca, Al, Fe silicate and therefore probably glauconitic clay.

To record planktonic foraminifera in the section, thirty-eight samples, collected at 50 cm intervals from the base of the section, were wet-sieved, dried and the 63-2 000 µm fraction examined. Abundances of planktonic foraminiferal taxa were visually estimated because infraspecies morphological variation made the quantitative abun-

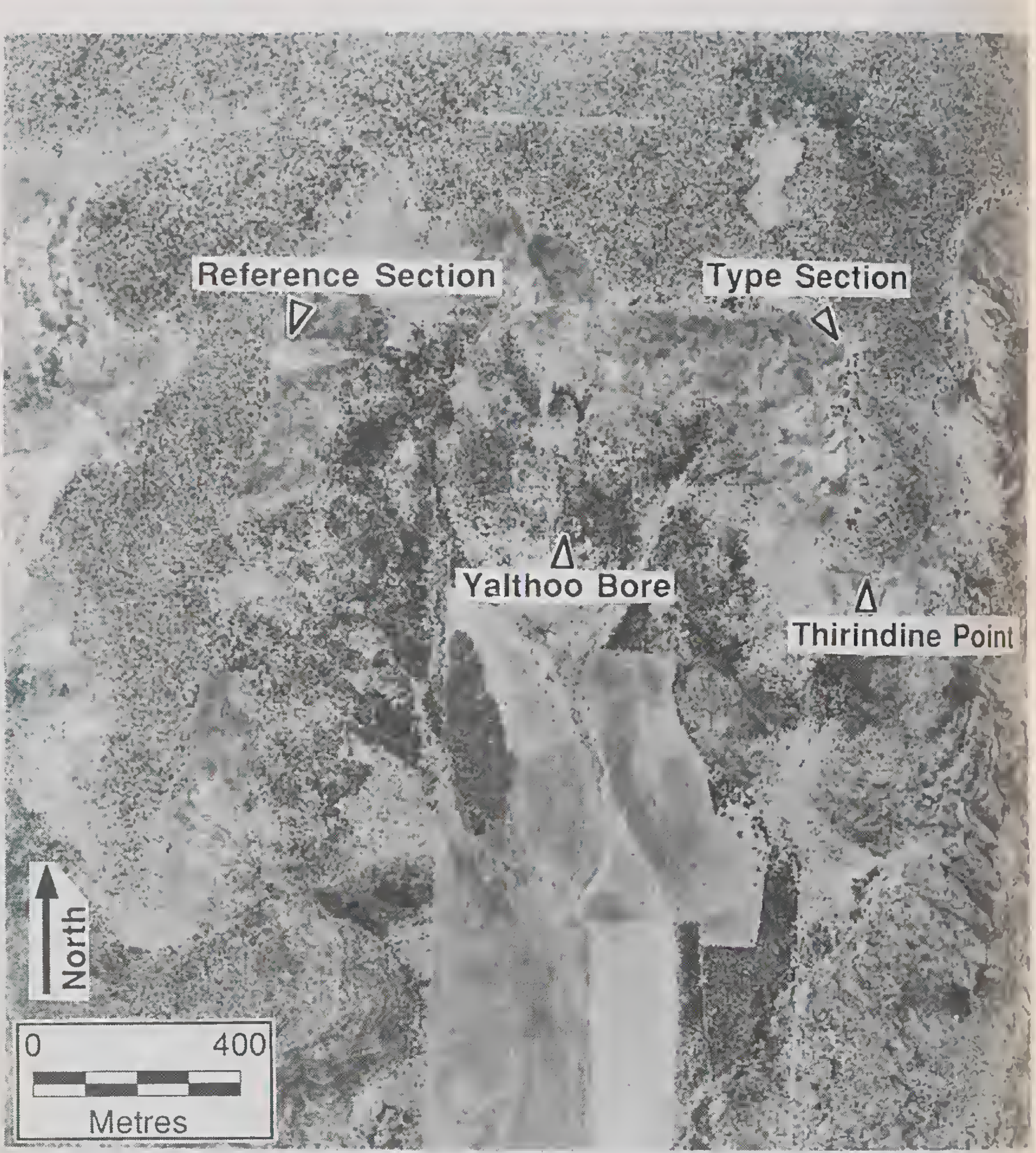

Figure 1 Aerial photograph of the lower Murchison River area showing the position of the reference section (enlargement of Photo. 5077 AJANA Run 11 [5043-5080] reproduced with permission of the Department of Lands Administration).

dance determination of some forms difficult. Thirteen of the samples were chosen at about two metre intervals to provide a record of the benthonic foraminifera. The 150-2 000 µm fraction of these samples were systematically picked and the numbers of specimen from each benthonic taxon was counted.

To provide additional age control in the section, strew slides containing abundant calcareous nannoplankton also were prepared from fresh material taken from the same levels as those systematically studied for foraminifera.

Lithostratigraphy

In the type area, the Toolonga Calcilutite disconformably overlies the Alinga Formation (Figure 2). Clarke and Teichert (1948) and Johnstone *et al.* (1958) placed the contact at the abrupt change in lithology from green glauconitic sandstone and siltstone to cream-coloured chalk where a thin but extensive layer of ovoid phosphatic nodules, which range from 3-10 cm in diameter, is present (Figure 3). The phosphatic nodule layer indicates very low sedimentation rates or an erosive event (Ames 1959, Kennedy and Garrison 1975, Kennett 1982) and suggests a disconformity between the underlying Alinga Formation and the Toolonga Calcilutite. Copp (1987) suggested that the Alinga Formation may extend into the Middle Turonian or younger in the type area based on the presence of biostratigraphically-useful calcareous nannoplankton recorded from the top of the Alinga Greensand, which indicates that the disconformity may range from Late Turonian to Early Santonian. The top of the Toolonga Calcilutite is covered by soil and calcrete and no contact with younger units is seen in the study area. The section is composed of three conformable lithostratigraphic units (Figure 3) which are distinctive in outcrop due to differing induration, colour and composition as described below. Units 1 & 2 may represent the 'Toolonga Chalk'; and Unit 3, the 'Second Gully Shale' of Clarke and Teichert (1948).

Unit 1. This disconformably overlies the Alinga Formation, is 50 cm thick and consists of fine-grained, glauconitic sand and white calcilutite. The glauconitic grains, 0.1-0.5 mm in diameter, have undulose irregular outlines indicating an authigenic origin. Some grains are globular which may indicate that they formed within foraminiferal tests. These contrast with the glauconite particles of the underlying Alinga Formation which are well rounded, apparently from being continually reworked and rolled along the bottom. Fish teeth are common in the lowest part of the unit. They are composed of insoluble phosphatic material (mainly apatite) and therefore would be concentrated by early selective dissolution of the nannoplankton / foraminiferal ooze on the seafloor.

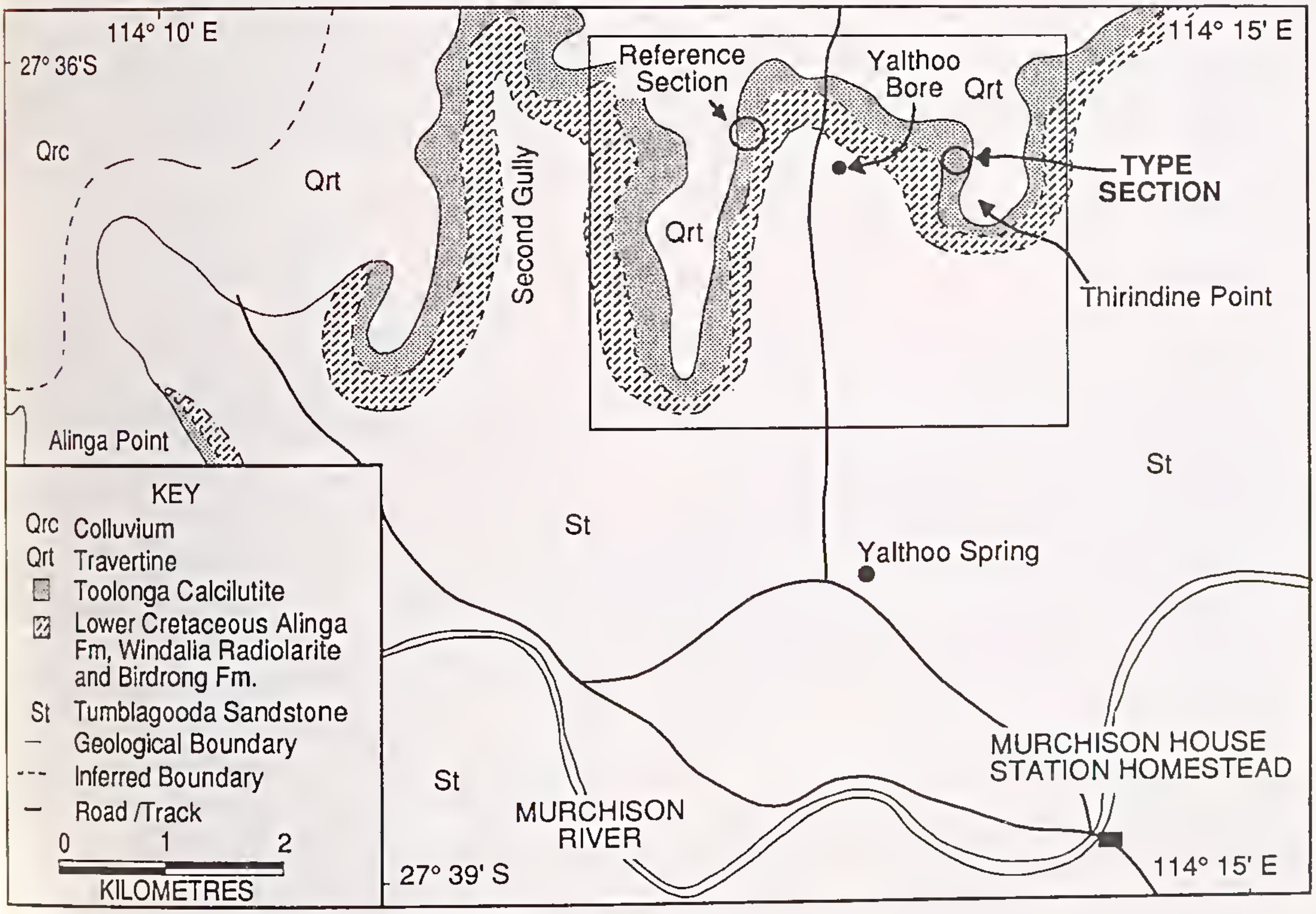

Figure 2 Geological map of the lower Murchison River area.

Unit 2. Conformably overlying Unit 1 is 8 m of white calcilutite and *Inoceramus* calcarenite characterized by an abundance and diversity of macrofossils. Fragments of *Inoceramus* are common as discontinuous bands 1-95 cm thick or as single randomly orientated specimens. Calcite prisms derived from the breakdown of *Inoceramus* are common constituents of the calcilutite and compose more than 50% of the 63-2 000 µm fraction in many of the samples. Individual peaks of sand-sized material seen in Unit 2 (Figure 3) correlate with *Inoceramus* rich horizons. Light yellow-brown phosphatic nodules, 1 cm in diameter, are present in three laterally extensive horizons 1 m, 2.9 m and 8.5 m above the phosphatic nodule horizon marking the Alinga Formation–Toolonga Calcilutite contact.

Unit 3. Conformably overlying Unit 2 is a 10 m section of marly greenish calcilutite. Unit 3 differs from Unit 2 in being less indurated. The greenish appearance of Unit 3 arises from the high proportion of glauconitic clay within the calcilutite. It is covered by weathered calcilutite and soil, and appears homogeneous due to intense bioturbation (which has obscured many of the smaller-scale features of bedding) and the lack of large *Inoceramus* fragments common to Unit 2. Calcite prisms derived from *Inoceramus* are rare in the first 2 m of Unit 3 and are absent above this level. A single, laterally extensive bed of chert nodules occurs 7.5 m above the Unit 2–Unit 3 boundary. The nodules are generally small and ovoid, although rare specimens are tabulate and up to 20 cm across. Chert nodules form more than one horizon in other exposures of the upper unit of the Toolonga Calcilutite within the area. When broken, the nodules consist of alternating light and dark brown layers of chert and minor inclusions of silicified chalk.

Chert nodules form by the early diagenetic replacement of carbonate by opaline silica below the sediment surface, and their shape depends on the morphology of the oxic-anoxic mixing zone (Clayton 1983, Maliva and Siever 1988). Because burrows alter the homogeneity of the sediment and the shape of the mixing zone, chert nodules are likely to develop within burrow forms (Bromley and Ekdale 1983, Clayton 1983, Felder 1983). Chert nodules in the type area are generally digitate or tabulate. Digitate nodules are cylindrical, up to 50 cm long and 10 cm in

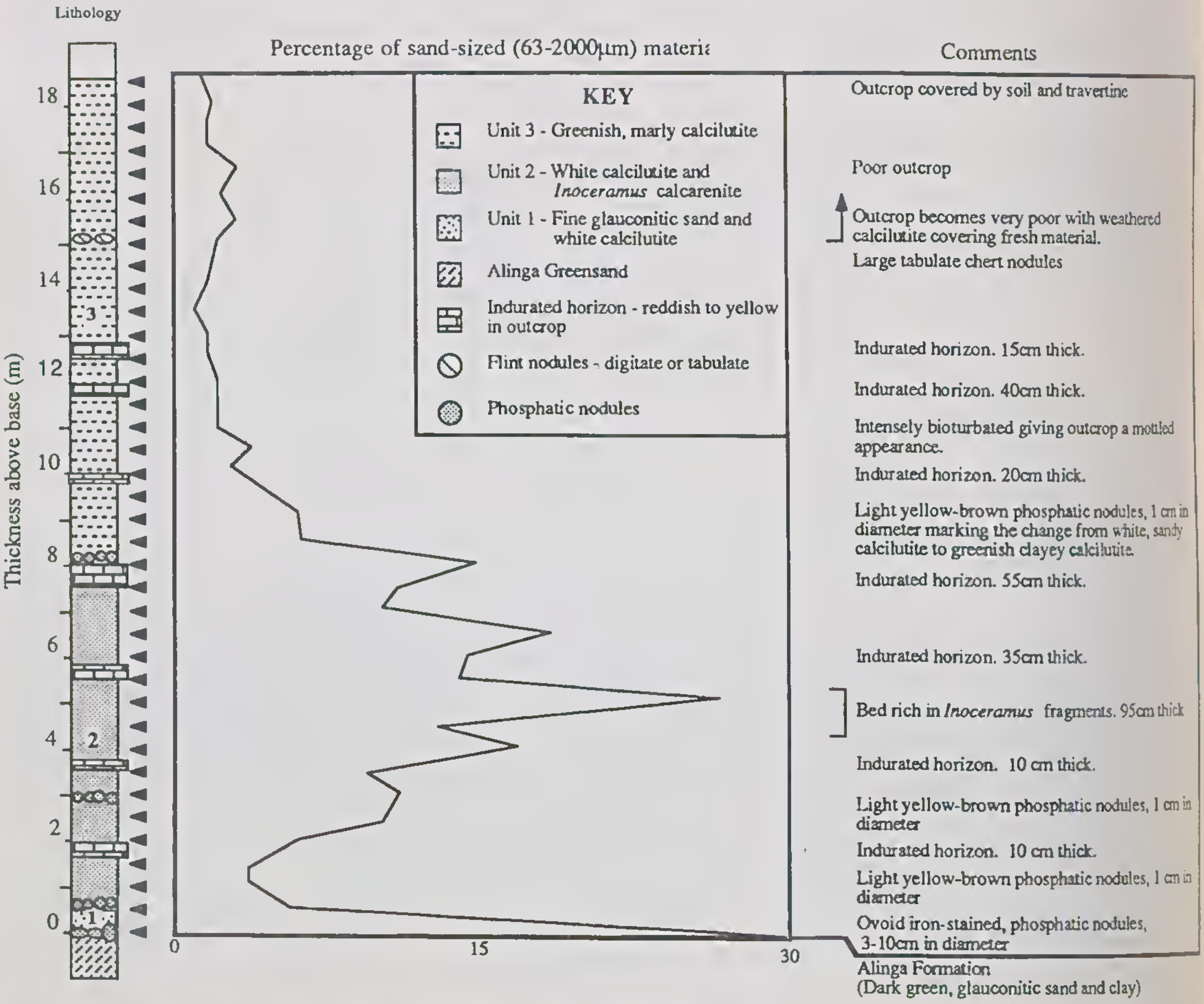

Figure 3 Lithostratigraphy of the reference section, Toolonga Calcilutite.

diameter, and tend to be perpendicular to bedding and appear to mimic other features seen in the Toolonga Calcilutite which are thought to have formed by the burrowing activites of irregular echinoids. Tabulate nodules are about 3 cm thick, up to 20 cm across, generally oval shaped, parallel to bedding, and are commonly associated with indurated horizons which may have restricted the oxic-anoxic mixing zone along the plane of bedding creating favourable conditions for the formation of chert nodules. Digitate nodules occur mainly in heavily bioturbated horizons where burrows would tend to channel the mixing zone into other horizons.

Although indurated horizons are common in both Unit 2 and Unit 3 (weathering to reddish-yellow layers, 10-55 cm thick, across the outcrop at about 2 m intervals), there is no evidence that these were hardgrounds similar to those described in English chalks by Bromley (1967), Hancock (1975), Kennedy and Garrison (1975), Scholle (1977) and Jarvis (1980). The lack of animal borings, scouring, phosphatization or encrustation by sessile organisms associated with the indurated beds indicates that the indurated horizons were not exposed on the seafloor at any time.

Dissolution of the Toolonga Calcilutite is minor, with the exception of Unit 1 which is heavily affected and is most apparent in the foraminiferal assemblage which includes mainly robust, thicker-walled rotaliids and agglutinated foraminiferal tests. Keeled planktonic foraminifera are affected by dissolution in the lower half of the section (Units 1 and 2), and the thin-walled portion of many tests is absent. Samples which show most dissolution contain abundant *Inoceramus* prisms and other mollusc fragments. Ostracods generally do not appear to be much affected by dissolution. In Unit 3, surfical solution of the chalk has produced small pits infilled with insoluble clayey material similar to pits described by Scholle (1977) in the European chalks.

Biostratigraphy

Macrofossils are common at all localities of the Toolonga Calcilutite in the Murchison River area. Faunal elements identified by the author with assistance from Dr K. McNamara and Mr. G. Kendrick of the Western Australian Museum are the serpulid worm *Serpula fluctuata* Sowerby; brachiopods *Trigonosemus acanthodes* Etheridge, *Magasella cretacea* Etheridge; bivalves *Pycnodonta ginginensis* Etheridge, *Inoceramus* sp., *Ostrea* sp.; crinoids *Marsupites testudinarius* (Schlotheim), *Marsupites* sp., *Uintacrinus* sp. A number of trace fossils, cidaroid echinoid spines and barnacles were recorded from the reference section but have not been identified to generic level.

Inoceramus occurs as (a) solitary, randomly orientated fragments or (b) 1-95 cm thick, laterally discontinuous horizons which appear to be lag deposits created by localized current activity as evidenced by their horizontal alignment and sorting. Entire valves are very rare and only two specimens were found in the type area. The larger *Inoceramus* clasts are confined to Unit 2, and only microscopic fragments and prisms are present in the lowest few metres of Unit 3. No fragments of *Inoceramus* were found in Unit 1.

Ossicles of the crinoid *Uintacrinus* are common in the lower half of the section where they form a clearly defined zone 2.5 m-5.5 m above the base of the section. No calicular plates identified as *Uintacrinus* were found in any of the exposures in the area. *Marsupites* calicular plates were found in sections throughout the area and form two distinct groups according to their size, ornamentation and distribution. The smaller, smooth form appears sporadically below the *Uintacrinus* zone and could not be identified to species level. The larger form, having radial striations on the upper surface, was tentatively identified as *Marsupites testudinarius* (Schlotheim) and occurs only above the *Uintacrinus* zone. Clarke and Teichert (1948) reported two species of *Marsupites* from the Toolonga Calcilutite in the Murchison River area: a smaller form resembling *Marsupites testudinarius* (Schlotheim) and a considerably larger, smooth, second type of plate. No specimens of this second form were found.

The oyster *Pycnodonta ginginensis* Etheridge is found throughout the section, most commonly as solitary specimens with an inflated dorsal valve, orientated parallel to bedding. Very rare, immature specimens were found attached to *Inoceramus* fragments.

Bioturbation is common throughout the section and three burrow forms are present. The first form is cylindrical, 1-2 cm in diameter, infilled with coarse-grained sediment. These burrows extend for 2-10 cm across the outcrop and are generally sub-parallel to the bedding. Their morphology indicates that they may have been formed by irregular echinoids. The second burrow form is common throughout the section, and consists of randomly oriented, cylindrical burrows about 1 cm in diameter which can be traced for 10-60 cm. The third burrow form is common in the upper part of the section and in the topmost 30 cm of the Alinga Formation It forms a branching meshwork of burrows, 1-2 mm in diameter and 1-5 cm long. All three forms appear to have be created by deposit feeding organisms.

Other macrofossils (such as the serpulid worm *Serpula fluctuata* Sowerby, brachiopods *Trigonosemus acanthodes* Etheridge, *Magasella cretacea* Etheridge, and the bivalve *Ostrea* sp.) appear to be randomly distributed within the section.

The section contains an abundant and diverse assemblage of generally well-preserved foraminifera. Planktonic foraminifera dominate the succession, with the exception of the lowest sample, and form 33-74% of the systematically-picked assemblages. The percentage of planktonic foraminifera rapidly rises from less than 1% in the lowest sample to about 65% 4.5 m above the base of the section. The abundance of planktonic foraminifera remains near this level until 14.5 m above the base, then gradually declines to 40% in the uppermost sample. The Globotruncanacea, Planomalinacea and Rotaliporacea are the dominant planktonic superfamilies; the Heterohelicacea are less common. The stratigraphic distribution of planktonic foraminiferal species is shown in Figure 4 and Table 1. Most of the forms are wide-ranging but notable exceptions are *Heterohelix papula* (Belford) and *Hastigerinoides simplex* (Morrow) which only occur in the first few metres of the section; *Globotruncana fornicata* (Plummer) ranges from 3.5-6.0 m and *Globotruncana arca* (Cushman) which ranges from 7.5-18.5 m. Another short ranging form, *Globotruncana* sp. (5.0-7.5 m) appears to be transitional between *G. fornicata* (Plummer) and *G.arca* (Cushman) but further work is required to examine any evolutionary trend.

Benthonic foraminifera are also abundant and diverse in the section. The stratigraphic distribution of benthonic foraminifera is shown in Table 2. The Order Rotaliida (Haynes 1981) dominates the assemblage at all levels with abundances ranging from 10-25% of the total assemblage. Excluding the lowest sample where selective dissolution has concentrated foraminifers with more robust tests, rotaliids comprise 77% of the assemblage. Other orders contribute less than 20% of the total assemblage.

It can be seen from the stratigraphic distribution of benthonic foraminifera (Table 2) that some forms abound

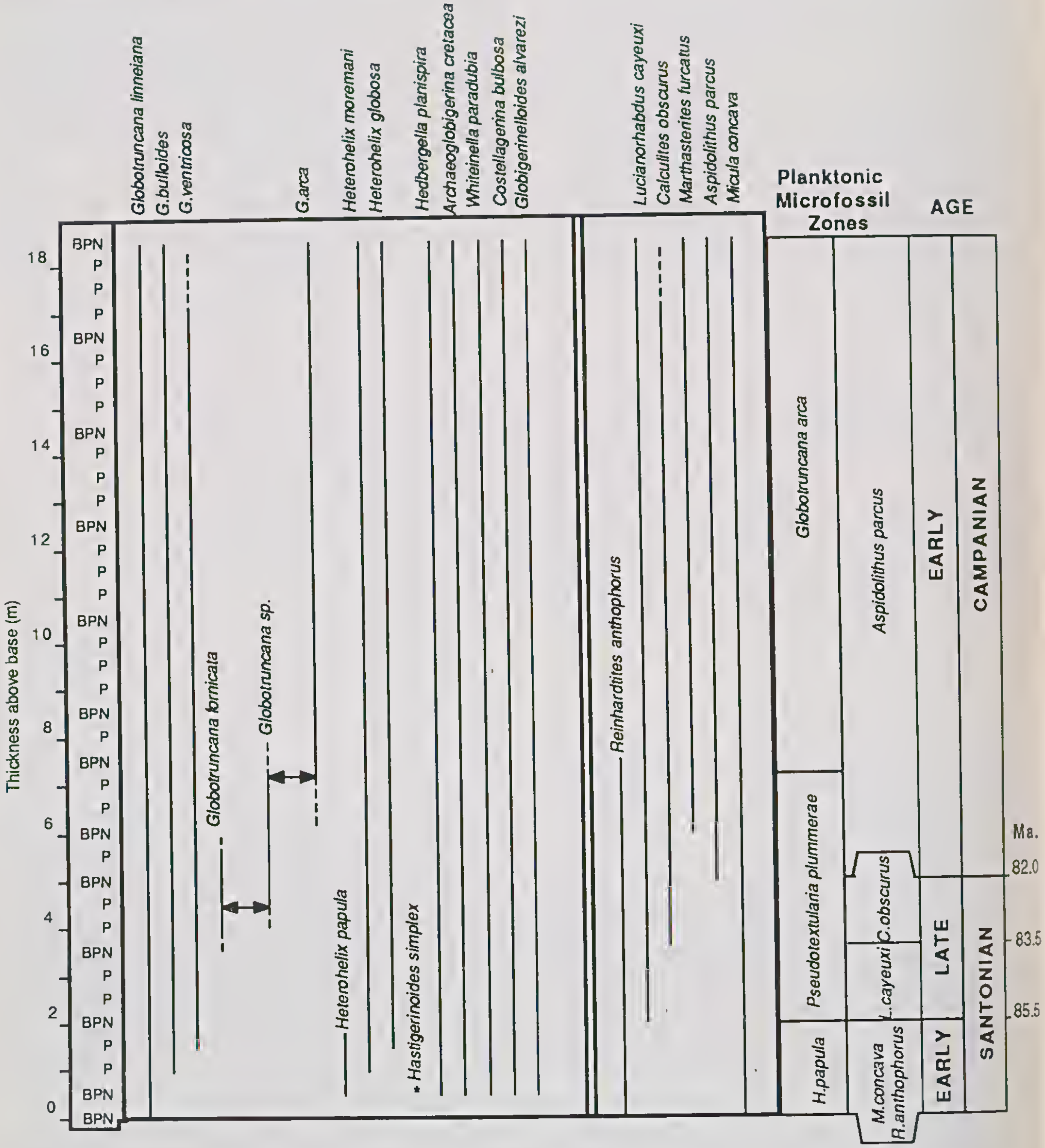

Figure 4 Stratigraphic distribution of planktonic foraminifera and biostratigraphically useful calcareous nannoplankton, and age assignment of the reference section. Positions of samples used in this study are shown (BPN—benthonic foraminifera, planktonic foraminifera and calcareous nannoplankton; P—planktonic foraminifera) and inferred species transitions indicated (◄–►).

Table 1

Stratigraphic distribution of planktonic foraminifera in the reference section, Toolonga Calcilutite. Species are listed by superfamilies as defined by Loeblich and Tappan (1988). The abundance of each taxon is expressed as rare (R), common (C), abundant (A) in a systematic pick or present x in a selective pick only.

	UNIT 1		UNIT 2						UNIT 3				
	0.0	0.5	2.0	3.5	5.0	6.0	7.5	8.5	10.5	12.5	14.5	16.5	18.5
HETEROHELICACEA													
Heterohelix globulosa			C	R	R	R	R	R	R	R	R	R	R
Heterohelix moremani			R	R	R	R	R	R	C	C	R	R	C
Heterohelix papula		C	R										
PLANOMALINACEA													
Globigerinelloides alvarezi			R	R-C	x	x	R	x	R-C	R-C		R-C	R
Hastigerinoides simplex		x											
ROTALIPORACEA													
Costellagerina bulbosa			R-C	R-C	R-C	R	x	x	R	R	R	R	
Hedbergella sp. aff. *H. planispira*		x	C	R	R	R	A	C	C	C	R	R	R
Whiteinella paradubia		x	C	R-C	R-C	C	R	x	x		R	R	R
GLOBOTRUNCANACEA													
Archaeoglobigerina cretacea		x	x	x	R	R	R		x	x	x		R
Globotruncana sp.					R-C	R	x						
Globotruncana arca							R	R	R	R	R	R	R
Globotruncana bulloides		R-C	R-C	R-C	R-C	C	R	R	R	x	x	x	x
Globotruncana fornicata				x	R-C	x							
Globotruncana linneiana	R	A	A	A	C	R-C	R	R-C	R	C	R	R	R
Globotruncana ventricosa			x	R	R	R-C	R	R	R	x	x	x	

within the reference section and have similar distribution patterns. These distribution patterns fall into three rough categories. The first group has abundances which are greatest in the lowest parts of the section (Unit 1) and include *Anomalinoides undulatus* Belford, *Clavulinoides trifidus* Belford, *Gaudryina* sp. cf. *G. laevigata* Franke and *Notoplanulina* sp. *Globorotalites micheliniana* (d'Orbigny), *Gyroidinoides noda* (Belford), *Lingulogavelinella insculpta* (Belford), *Marssonella oxycona* (Reuss), *Osangularia* sp., *Verneuilina parri* Cushman and *Pyramidina szajnochae* (Gryzbowskii) form the second group which have the greatest abundance in the middle of the section (Unit 2). The third is those forms which are most abundant within the upper half of the section (Unit 3): *Anomalinoides erikdalensis* (Brotzen), *Dorothia bulleta* (Carsey), *Eponides concinna* Brotzen, *Eponides diversus* Belford, *Goësella chapmani* Cushman, *Pullenia cretacea* Cushman, *Spiroplectammina gryzbowskii* Frizzell, *Spiroplectammina paula* Belford.

The species distribution described above is thought to be environmentally controlled. Unit 1 and Unit 3 were deposited under conditions where bottom waters were slightly depleted in dissolved oxygen as inferred by the low numbers of calcareous metazoans and the dominance of smaller burrows (Rhoads and Morse 1971, Savdra and Bottjer 1986). The level of dissolved oxygen was high during deposition of Unit 2 as shown by the abundance and diversity of calcareous macrofossils. Other differences in the foraminiferal assemblages may be related to bathymetry.

Calcareous nannoplankton abound throughout the reference section. Only the stratigraphic distribution of those calcareous nannoplankton essential for age determination is recorded (Figure 4), although the total assemblage probably consists of up to 60 species. The calcareous nannoplankton examined from the reference section are: *Aspidolithus parcus* (Stradner), *Calculites obscurus* Deflandre, *Lucianorhabdus cayeuxi* Deflandre, *Marthasterites furcatus* (Deflandre), *Micula concava* (Stradner) and *Reinhardtites anthophorus* (Deflandre). Their stratigraphic distribution is shown on Figure 4.

A list of foraminifera and calcareous nannoplankton identified from the reference section is given in Appendix 1.

Age assignment

A Santonian age for the Toolonga Calcilutite was inferred by Clarke and Teichert (1948) from the presence of the pelagic crinoids *Uintacrinus* and *Marsupites*. Integrated planktonic foraminifera and calcareous nannoplankton biostratigraphy has resulted in a detailed age determination for the Toolonga Calcilutite in the type area (Figure 4). Planktonic foraminifera and calcareous nannoplankton identified within the reference section enables application of the unpublished zonation of Rexilius (1984; Figure 5 herein). The calcareous nannoplankton zonation shown in Figure 5 has been modified from Rexilius (1984) to include the *Reinhardtites anthophorus* zone, *Calculites obscurus* zone and *Calculites ovalis* zone of Sissingh (1977). The base of the Toolonga Calcilutite contains the biostratigraphically important planktonic foraminifera *Heterohelix papula* (Belford), which Rexilius (1984) used as a zonal index for his *Heterohelix papula* zone (early Santonian) and the calcareous nannoplankton *Reinhardtites anthophorus* (Deflandre) and *Micula concava* (Stradner) he used as the zonal index species for the *Reinhardtites anthophorus* zone (early Santonian). Rexilius (1984) used the first appearance of *Rugoglobigerina rugosa* (Plummer) as the datum marking the base of his *Rugoglobigerina rugosa* zone (middle Campanian). The absence of *R. rugosa* (Plummer)

Table 2

Stratigraphic distribution of benthonic foraminifera in the reference section, Toolonga Calcilutite. Species are listed b superfamily as defined by Loeblich and Tappan (1988) and expressed as a percentage of the total benthon foraminiferal assemblage. Stratigraphic thickness is given in metres above base of the Toolonga Calcilutite.

	UNIT 1		UNIT 2						UNIT 3				
	0.0	0.5	2.0	3.5	5.0	6.0	7.5	8.5	10.5	12.5	14.5	16.5	18.5
AMMODISCACEA													
Ammodiscus cretacea	..	..	..	..	..	..	..	..	..	..	..	x	
Glomospirella sp.	..	..	..	..	..	..	..	..	..	..	..	x	.
RZEHAKINACEA													
Silicosigmoilina sp.	..	1	..	..	..	..	..	x	x	x	x	..	..
LITUOLIDACEA													
Haplophragmoides sp. cf. *H. kirki*	1	x	..	..	..	..	..	..	..	..	..	..	..
Ammobaculites sp. A	..	..	x	..	..	..	..	..	..	..	..	..	..
Ammobaculites sp. B	..	x	x	x	x	..	..	x	x	x	..	..	..
SPIROPLECTAMMINACEA													
Spiroplectammina grzybowskii	..	2	x	..	x	..	2	5	..	9	6	10	4
Spiroplectammina laevis	..	..	..	..	..	x	x	x	3	3	x	3	2
Spiroplectammina paula	..	..	..	..	..	..	..	x	x	3	11	6	4
VERNEUILINACEA													
Gaudryina sp. cf. *G. laevigata*	1	7	6	13	..	x	..	x	x	..	..	..	..
Spiroplectinata compressiuscula	2	1	..	..	..	x	x	..	..	..	..	..	..
Verneuilina parri	..	..	x	1	x	x	5	3	3	..	..	x	..
TEXTULARIACEA													
Clavulinoides trifidus	2	6	x	..	..	..	..	..	..	..	..	..	..
Dorothia bulleta	..	..	3	2	x	4	..	..	..	..	x	9	..
Goesella chapmani	..	x	1	1	x	x	x	4	3	5	4	4	5
Marssonella oxycona	6	10	20	14	6	4	7	x	16	8	6	x	2
MILIOLACEA													
Spiroloculina cretacea	..	..	..	..	3	..	..	x	..	..	x	..	.
NODOSARIACEA													
Astacolus sp. A	..	..	..	..	..	x	x	..	..	..	..	..	.
Astacolus sp. B	..	..	..	..	..	..	..	..	..	x	..	..	..
Berthelinopsis sp.	..	..	..	..	x	..	..	..	..	..	..	..	..
Bullapora laevis	..	..	..	..	..	..	..	x	x	..	..	..	..
Citharina geisendorferi	..	..	x	..	..	..	..	..	..	..	..	..	.
Citharina multicostata	..	x	x	..	..	..	..	..	..	..	..	..	.
Citharina suturalis	..	..	x	..	2	..	..	x	..	..	..	..	.
Dentalina admodicosta	..	..	..	..	..	..	x	x	..	..	..	x	x
Dentalina marcki	..	x	..	..	..	..	..	..	..	..	..	..	..
Frondicularia costulifera	..	..	..	..	2	..	3	..	..	..	..	..	..
Frondicularia disjuncta	..	..	x	..	..	..	..	..	..	..	x	..	..
Frondicularia mucronata	1	x	..	..	..	..	..	..	..	..	..	..	..
Frondicularia planifolium	..	..	..	1	2	..	..	..	..	..	..	..	.
Frondicularia verneuiliana	..	..	..	..	..	x	x	x	..	..	..	..	..
Frondicularia teuria	..	..	x	..	..	..	x	x	..	..	..	..	..
Globulina sp.	..	x	..	..	2	..	..	..	..	..	..	..	..
Laevidentalina cylindroides	..	..	x	..	2	..	x	x	..	..	x	x	..
Laevidentalina gracilis	..	..	..	..	..	..	x	..	x	..	..	2	x
Laevidentalina luma	..	..	x	..	2	..	x	x	..	x	x	..	..
Laevidentalina sp.	1	..	x	1	..	x	..	x	..	..	x	..	..
Lagena hexagona	..	..	..	..	..	..	..	..	..	..	..	..	
Lagena sp.	..	..	..	..	3	..	..	..	..	..	..	..	..
Lenticulina macrodiscus	..	..	1	..	2	..	..	..	..	..	..	..	..
Lenticulina rotulata	2	..	..	..	3	x	x	x	3	3	x	..	x
Lenticulina sublobatus	..	..	..	1	2	..	..	..	..	..	..	..	..
Lenticulina sp.	3	3	3	2	2	..	..	x	x	..	x	..	x
Marginulina sp.	..	..	x	4	..	..	..	..	..	..	..	..	..
Neoflabellina praereticulata	..	..	..	..	..	..	..	..	x	x	x	x	x
Neoflabellina rugosa	..	..	x	2	2	x	x	..	..	..	..	..	..
Nodosaria affinis	..	..	x	..	..	..	..	..	..	..	..	..	..
Nodosaria limbata	..	..	..	..	x	x	..	..	x	..	..	..	x
Nodosaria obscura	1	x	..	..	..	..	..	..	..	..	..	..	..
Nodosaria prismatica	..	..	x	1	..	..	..	..	..	..	..	..	..
Palmula pilulata	..	..	..	1	2	x	..	..	..	..	..	..	..
Planularia sp.	..	..	..	..	..	6	..	..	3	..	..	..	x
Pyrulina sp.	..	..	..	..	..	..	..	x	x	..	x	..	..
Ramulina aculeata	2	..	x	1	..	..	x	x	..	x	x	x	..
Ramulina pseudoaculeata	..	x	..	1	2	x	..	..	..	x	7	4	x
Saracenaria sp.	..	..	3	..	..	..	..	..	..	..	..	..	..

Table 2—*continued*

Stratigraphic distribution of benthonic foraminifera in the reference section, Toolonga Calcilutite. Species are listed by superfamily as defined by Loeblich and Tappan (1988) and expressed as a percentage of the total benthonic foraminiferal assemblage. Stratigraphic thickness is given in metres above base of the Toolonga Calcilutite.

	UNIT 1		UNIT 2						UNIT 3				
	0.0	0.5	2.0	3.5	5.0	6.0	7.5	8.5	10.5	12.5	14.5	16.5	18.5
BOLIVINACEA													
Bolivinoides strigillatus	..	..	..	..	..	..	x	x	..	..	..	..	..
LOXOSTOMATACEA													
Loxostomum sp. cf. *L. eleyi*	..	..	..	1	2	x	x	x	x	x	..	..	..
EOUVIGERINACEA													
Eouvigerina sp. cf. *E. americana*	..	..	..	..	..	..	x	x	x	..	..	x	x
Eouvigerina gracillis	..	1	x	..	..	..	x	x	x	x	x	2	2
PLEUROSTOMELLACEA													
Ellipsoglandulina sp.	..	..	..	..	..	..	..	..	..	..	x	..	..
Ellipsoidella binaria	1	x	1	..	..	..	..	x	x	x	..	..	..
Ellipsoidella solida	1	x	..	..	..	..	..	x	..	x	x	..	..
TURRILINACEA													
Praebulimina reussi	..	..	..	..	2	x	x	x	x	x	x	x	x
Pyramidina szajnochae	7	38	1	12	x	2	11	26	9	x	..	..	..
DISCORBACEA													
Eponides concinna	x	10	11	4	7	7	x	6	9	9	16	7	25
Eponides diversus	1	3	..	4	..	12	..	..	..	x	7	7	8
PLANORBULINACEA													
Carpentaria conica	..	..	..	..	..	..	..	..	..	x	x	x	..
Carpentaria globosa	..	..	..	..	..	..	..	..	x	x	x	..	..
Cibicides excavata	..	..	..	..	..	..	x	x	3	x	x	..	..
Cibicides ribbingi	..	..	..	..	..	..	..	x	x	..	..	..	..
Cibicides sp.	..	..	..	..	..	..	x	x	x	..	..	..	..
ASTERIGERINACEA													
Nuttallinella coronula	..	..	..	..	..	..	x	x	x	..	..	..	..
NONIONACEA													
Pullenia cretacea	2	1	..	..	3	..	x	4	..	6	5	7	4
CHILOSTOMELLACEA													
Anomalinoides erikdalensis	6	1	1	13	31	4	x	15	19	28	29	32	30
Anomalinoides undulatus	46	8	2	4	7	x	..	..	..	..	..	..	..
Globorotalites micheliniana	x	x	..	..	..	..	15	x	..	..	..	..	..
Gyroidinoides noda	2	9	17	15	8	16	18	18	15	x	7	9	6
Lingulogavelinella insculpta	..	..	..	..	11	46	11	16	x	17	14	7	5
Lingulogavelinella sp.	..	..	..	..	x	..	..	..	..	..	..	..	..
Notoplanulina sp.	15	22	26	1	..	..	..	..	..	..	..	x	..
Osangularia sp.	..	..	..	..	..	6	29	..	15	7	..	..	..
Quadrimorphina allomorphinoides	..	..	..	..	x	..	x	..	x	x	x	..	..
Stensioeina truncata	..	..	..	..	x	..	..	..	..	..	..	..	..
Unidentified	1						x				x		x

in the section suggests that the youngest possible age for the section is within the *Globotruncana arca* zone (early Campanian). The presence of *Marthasterites furcatus* (Deflandre) in the highest sample taken from the reference section indicates that the section can be no younger than the *Aspidolithus parcus* zone (early Campanian).

Rate of sediment accumulation

The substrate was probably a thick planktonic foraminiferal / calcareous nannoplankton ooze by analogy to modern calcareous oozes. The oyster, *Pycnodonte gingineusis* Etheridge, normally an encrusting taxon, may have adapted to reclining in the soft substrate by the development of inflated valves. Other evidence includes the composition of the faunal assemblage, including taxa such as *Stensioeina* and *Bolivinoides* (foraminifera), *Inoceramus* (pelecypod) and trace fossils which are typical of soft bottom conditions (Reid 1962). An estimation of the rate of deposition can be made by correlation of the calcareous nannoplankton and planktonic foraminiferal biostratigraphy with the time scales given in Haq *et al.* (1987), although these correlations are subject to error given the number of direct comparisons available. The inferred rate of sedimentation, assuming a post-depositional compaction factor of 10% (estimated for European chalks by Scholle 1977) increases up the section and is calculated for each calcareous nannoplankton zone. The base of the *Reinhardtites anthophorus* zone was not recognized but the zone is assumed to be complete giving a depositional rate of 28 cm/million years. The *Lucianorhabdus cayeuxi* zone was recognized from 2-3.5 m in the reference section giving a depositional rate of 83-220 cm/million years. The *Calculites obscurus* zone was recognized from 3.5-5 m in the reference section giving a depositional rate of 110-220 cm/million years. The top of the *Aspidolithus parcus* zone was not recognized but the zone is assumed to be complete giving a depositional rate of 990-1 100 cm/ million years. Hiatuses may be recorded in the reference section as (a) layers of phosphatic nodules (Figure 3) which Kennedy and Garrison (1975) and Kennett (1982) state are formed during periods of low or negative sedimentation or (b) *Inoceramus* rich horizons which may have formed as lag deposits.

Bathymetry

The presence of glauconite and phosphate within the section can be used to infer bathymetry. Bromley (1967) states that warm shallow water between 30 m and 300 m is particularly favourable for phosphate formation. Glauconite accumulates in modern oceans between 75 and 500 m, and mostly between 100 and 200 m (Odin and Stephen 1982).

Characteristics of the foraminiferal assemblage also were used for bathymetric determinations. The use of Cenozoic benthonic foraminifera in delineating bathymetry has been extensively documented but there are few studies of pre-Cenozoic bathymetric zonation because the significance of taxa is uncertain. Bathymetric models at the generic and species level for the Cretaceous are based on the homeomorphic comparison of Cretaceous and recent forms. The known bathymetric trends of Cretaceous species and genera were compared to the abundance groupings of benthonic foraminifera described in this study to assist in the determination of bathymetric conditions. Benthonic foraminifera indicate that deposition occurred in an epicontinental sea no shallower than ca. 100-200 m (outer neritic depths) and no deeper than ca. 200-500 m (upper bathyal depths). [It should be noted here that the terms outer neritic and upper bathyal are used to describe a bathymetric range and should not be confused with outer shelf and upper slope conditions because the Toolonga Calcilutite was deposited on a flat-lying epi-continental marine plain.] At the commencement of deposition, upper bathyal conditions prevailed. A decline in depth to outer neritic conditions, as shown by the foraminiferal assemblage, occurred about 6.0 m above

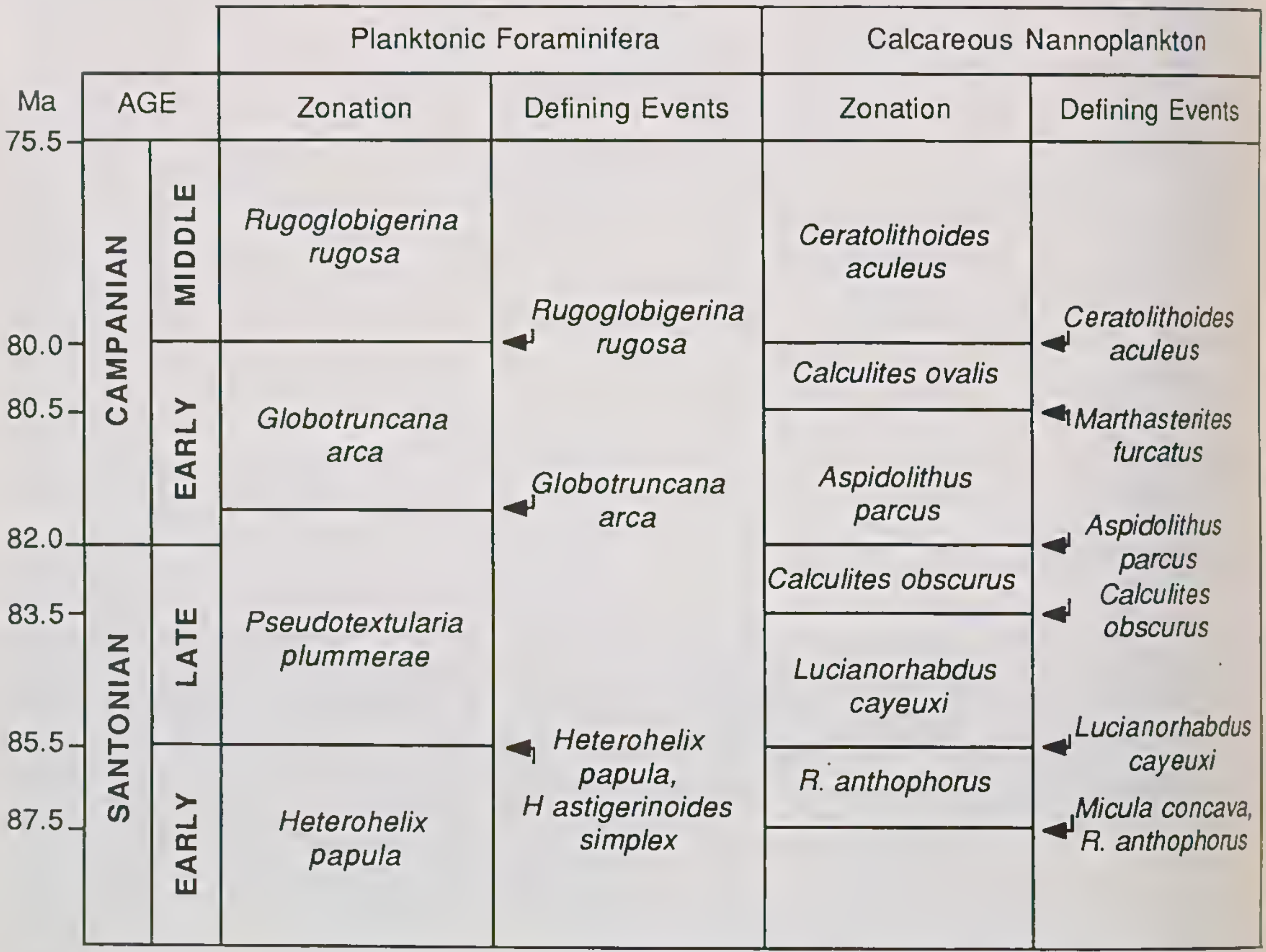

Figure 5 Planktonic foraminiferal and calcareous nannoplankton zonation used in this paper (after Rexilius 1984, pers. comm. 1988 and Sissingh 1977) with reference to radiometric dates given in Haq et al. (1987). (↲ first appearance, ↰ last appearance).

the base of the section, coinciding with a rapid increase in the rate of deposition. Depth of deposition increased to upper bathyal from 10.5-14.5 m and then gradually declined to outer neritic depths thereafter. Rescrictions on the depth of deposition are evident from a study of the tectonics of the area. The Tooloonga Calcilutite was deposited on a passive margin and therefore the depth of deposition was controlled by eustatic sea level rises, which were shown by Haq *et al.* (1987) to be in the range of 180-250 m for the Santonian–Campanian interval.

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Appendix

The following list of foraminiferal and calcareous nannoplankton species present in the Toolonga Calcilutite is given in alphabetical order. The specimens listed here are housed in the Micropalaeontological Collection, Geology Department, University of Western Australia.

Benthonic Foraminifera

Ammobaculites sp. A
Ammobaculites sp. B
Ammodiscus cretacea (Reuss)
Anomalinoides erikdalensis (Brotzen)
Anomalinoides undulatus Belford
Astacolus sp. A
Astacolus sp. B
Berthelinopsis sp.
Bolivinoides strigillatus (Chapman)
Bullapora laevis (Sollas)
Carpentaria conica (Belford)
Carpentaria globosa (Belford)
Cibicides sp.
Cibicides excavata Brotzen
Cibicides ribbingi Brotzen
Citharina geisendorferi (Franke)
Citharina multicostata d'Orbigny
Citharina suturalis (Cushman)
Clavulinoides trifidus Belford
Dentalina admodicostata Belford
Dentalina marcki Reuss
Dorothia bulleta (Carsey)
Ellipsoglandulina sp.
Ellipsoidella binaria Belford
Ellipsoidella solida (Brotzen)
Eouvigerina sp. cf. *E. americana* Cushman
Eouvigerina gracilis Cushman
Eponides concinna Brotzen
Eponides diversus Belford
Frondicularia costulifera Belford
Frondicularia disjuncta Belford
Frondicularia mucronata Reuss
Frondicularia planifolium Chapman
Frondicularia teuria Finlay
Frondicularia verneuiliana d'Orbigny
Gaudryina sp. cf. *G. laevigata* Franke
Globorotalites micheliniana (d'Orbigny)

Globulina sp.
Glomospirella sp.
Goësella chapmani Cushman
Gyroidinoides noda (Belford)
Haplophragmoides sp. cf. *H. kirki* Wickenden
Laevidentalina sp.
Laevidentalina cylindroides Reuss
Laevidentalina gracilus (d'Orbigny)
Laevidentalina luma Belford
Lagena sp.
Lagena hexagona (Williamson)
Lenticulina sp.
Lenticulina macrodiscus (Reuss)
Lenticulina rotulata Lamarck
Lenticulina sublobatus (Reuss)
Lingulogavelinella sp.
Lingulogavelinella insculpta (Belford)
Loxostomum eleyi (Cushman)
Marginulina sp.
Marssonella oxycona (Reuss)
Neoflabellina praereticulata Hilterman
Neoflabellina rugosa (d'Orbigny)
Nodosaria affinis Reuss
Nodosaria limbata d'Orbigny
Nodosaria obscura Reuss
Notoplanulina sp.
Nuttallinella coronula (Belford)
Osangularia sp.
Palmula pilulata Cushman
Planularia sp.
Praebulimina reussi (Morrow)
Pullenia cretacea Cushman
Pyramidina szajnochae (Gryzbowskii)
Pyrulina sp.
Quadrimorphina allomorphinoides (Reuss)
Ramulina aculeata (d'Orbigny)
Ramulina pseudoaculeata (Olsson)
Saracenaria sp.
Silicosigmoilina sp.
Spiroloculina cretacea Reuss
Spiroplectammina gryzbowskii Frizzell
Spiroplectammina laevis (Roemer)
Spiroplectammina paula Belford
Spiroplectinata compressiuscula (Chapman)
Stensioeina truncata Belford
Verneuilina parri Cushman

Planktonic Foraminifera

Archaeoglobigerina cretacea (d'Orbigny)
Costellagerina bulbosa (Belford)
Globigerinelloides alvarezi (Eternod Olvera)
Globotruncana sp.
Globotruncana arca (Cushman)
Globotruncana bulloides Vogler
Globotruncana fornicata (Plummer)
Globotruncana linneiana (d'Orbigny)
Globotruncana ventricosa White
Hastigerinoides simplex (Morrow)
Hedbergella sp. aff. *H. planispira* (Tappan)
Heterohelix globulosa (Ehrenberg)
Heterohelix moremani (Cushman)
Heterohelix papula (Belford)
Whiteinella paradubia (Sigal)

Calcareous Nannoplankton

Aspidolithus parcus (Stradner)
Calculites obscurus Deflandre
Lucianorhabdus cayeuxi Deflandre
Marthasterites furcatus (Deflandre)
Micula concava (Stradner)
Reinhardtites anthophorus (Deflandre)

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New data on the Permian crinoid family Calceolispongiidae in Western Australia

Curt Teichert

Department of Geological Sciences, University of Rochester, Rochester, NY 14627, USA

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Abstract

Previously published data on the geographic distribution and stratigraphic range of members of the crinoid family Calceolispongiidae in the Permian of Western Australia are updated and a census of all recorded occurrences of Western Australian species, named as well as unnamed, is taken. Representatives of the family are found throughout a maximum thickness of approximately 2 300 m of sedimentary rocks, ranging in age through the entire Early Permian. The family contains at least three genera, only two of which have been named. Total number of species seems to be in the vicinity of 30, of which 15 have been named and described.

Introduction

In 1949, I published a monographic treatment of all then known Western Australian species of a highly unusual Permian crinoid genus, *Calceolispongia*. This monograph was based mostly on material collected by me and students on numerous field trips to the northern part of the Perth Basin, to various parts of the Carnarvon Basin, and to the Canning Basin, carried out from 1938 until mid-1941. My investigations were made at a time when no topographic maps of these areas existed and before a code of stratigraphic nomenclature was introduced in Australia. Consequently, localities had to be identified with reference to local landmarks in areas where named geographic features were few. The unexpectedly great thickness of Permian rocks, especially in the Carnarvon Basin, made it necessary to name numerous rock units, previously unrecognized, and for this purpose I fell back on the somewhat antiquated stratigraphic terminology then in use in Australia. Thus, I used the term "stage" for rock units for which the use of "formation" is now mandatory, the term "series" for what is now "group," and I used fossil names for rock units (e.g., "*Calceolispongia* stage" for what I later named Wandagee Formation). The first version of an Australian Code of Stratigraphic Nomenclature was not published until 1948 (Glaessner *et al.* 1948), and the first attempt at modernizing the nomenclature of some of the Permian rock units in Western Australia was not made until 1950 (Teichert 1950).

Now, detailed topographical and geological maps of many areas studied by me in the distant past are available, thanks largely to the efforts of the Bureau of Mineral Resources, Geology and Geophysics and the Geological Survey of Western Australia, and most of the stratigraphic nomenclature in the sedimentary basins has been formalized to meet the requirements of the Australian Code of Stratigraphic Nomenclature (Teichert, 1950; Condon 1967; van de Graaff *et al.* 1977; Hocking *et al.* 1980; Hocking 1985, 1988). It is, therefore, now possible to update and refine both geographical and stratigraphical occurrence data for most of the species described by me in 1949 and it is the purpose of this communication to supply this kind of information. The vertical range of most species of *Calceolispongia* is rather restricted. In the classical stratigraphic section along the Minilya River on Wandagee Station (see Teichert 1949, fig. 13) species follow each other in stratigraphic succession, most of them being restricted to beds only a few tens of metres, or less, thick. Most species of *Calceolispongia* thus fulfill the conditions for good index fossils.

In my monograph in 1949, I expressed hope that it "will furnish a useful basis for additional and more detailed work when the geographic distribution and earlier geologic history of *Calceolispongia* are better known." Alas, this hope has not been fulfilled. In 1954, I described a new genus, *Jimbacrinus*, from the Carnarvon Basin and proposed the family Calceolispongiidae to include this genus, together with *Calceolispongia*. In 1979, Willinck described a number of species of *Calceolispongia* from Queensland, New South Wales, and Tasmania, none of them identical with any Western Australian species. In fact, after 1954 no further addition to the taxonomy of the Calceolispongiidae in Western Australia was made until 1987, when Webster redescribed two species of *Calceolispongia* from the Callytharra Formation and added one indeterminate species from the same formation. In 1990, Webster described a new species of *Jimbacrinus* from the Wandagee Formation.

Series	Stage	Substage	Group	Formation		
U.PERM.	Guad.		Kennedy	Binthalya	-----------	
				Mungadan	-----------	
LOWER PERMIAN	Roadian			Coolkilya	*C. hindei, C. robusta, C.* sp. ind. B, *C.* sp ind. C.	
			Byro	Baker	?*C.* sp. ind. D.	
				Nalbia	*C.* sp. ind. A, *C.* sp. (Condon, 1967)	
	Artinskian	Baigendzhinian		Wandagee	60-145m *C. spectabilis* 50-56m *C. multiformis* 45-55m *C. rubra* 25-35m *C. abundans* 0-50m *C. rotundata* 0-25m *C. elegantula*	*Jimbacrinus minilyaensis* from unrecorded horizon
				Quinnanie	*C.* sp. ind. E, *C.* sp. (Condon, 1967)	
				Cundlego	*C. truncata, Jimbacrinus bostocki*	
				Bulgadoo	*C. acuminata*	
				Mallens	*C. acuminata, C.* sp. (Dickens in Condon, 1967)	
				Coyrie	*C. barrabiddiensis, C.* sp. ind. F.	
			Wooramel	Billidee	*C.* sp. (Condon, 1967)	
				Moogooloo	------------	
		Akt.		Cordalia	------------	
	Sakmar.	Ster.		Callytharra	*C. digitata, C. spinosa;* Calceolispongiidae? gen. et sp. ind. (Webster, 1987)	
		Tast.	Lyons	Carrandibby	Calceolispongiidae gen. nov., sp. nov. (Dickins & Thomas, 1959)	
	Asselian			undivided	Calceolispongiidae gen. nov., sp. nov. (Dickins & Thomas, 1956) *C.* spp. (Condon, 1967)	

Figure 1 Distribution of Calceolispongiidae in the Permian strata of the Carnarvon Basin. (C = *Calceolispongia*, Akt. = Aktastian, Guad. = Guadalupian, Ster. = Sterlitamakian, Tast. = Tastubian).

Meanwhile, Guppy *et al.* (1950), Dickins and Thomas (1956, 1959), Condon (1967), and Dickins *et al.* (1977) had recorded numerous occurrences of Calceolispongiidae, including at least one new genus, from new localities in the Carnarvon and Canning Basins and extended the stratigraphic range of the family downward into the Lyons Group. Unfortunately, most of these species remained undescribed and unnamed. In order to make the updating of information on the Calceolispongiidae as complete as possible, I have culled all the information from the published literature to present a new and improved picture of the stratigraphic distribution of the family in the Permian rocks of Western Australia, including many unnamed species and, possibly, genera.

In the following are listed all occurrences of Calceolispongiidae presently recorded in print from Western Australia. No descriptions or discussions are supplied for species that have already been adequately described and discussed in easily accessible publications (Teichert 1949, 1954; Webster 1987, 1990).

Stratigraphic Distribution of the Calceolispongiidae in Western Australia

The maximum thickness of Permian rocks in the Carnarvon Basin is about 3 500 m, but this figure is probably reached only in the northern half of the basin; here, most of the recorded species of Calceolispongiidae occur throughout the lowermost 2 300 m of the Permian section. The vertical distribution of species, named and unnamed, of the calceolispongiids, including at least one unnamed new genus, is shown on Figure 1. The stage correlation is that proposed by Glenister *et al.* (1985). Rather unexpectedly, the family makes its first appearance in the Lyons Group which is of glacigene origin. Condon (1967) divided the Lyons Group into seven formations, from four of which he reported presence of unnamed species of Calceolispongiidae. However, van de Graaff *et al.* (1977) were unable to map these formations on the ground; they proposed to reduce the rank of the Lyons Group to that of Formation, reducing Condon's seven formations to the status of local members. Hocking (1985), on the other hand, reinstated the Lyons as a Group, including in it as basal unit the Harris Sandstone of Carboniferous age (not shown in Figure 1) and as top unit the Carrandibby Formation. He regarded the bulk of the Lyons Group above the Harris Sandstone as being Early Permian (Sakmarian) in age.

Although the relative stratigraphic position of the various species of Calceolispongiidae in the Lyons Group is not know, it is interesting to note the environments in which they lived. An unnamed species of *Calceolispongia* is mentioned from the "Dumbaro siltstone" which Condon (1967, p. 26) described as having been deposited "in water from floating ice derived from continental glaciers or a continental ice sheet." Another species of *Calceolispongia* is reported from the "Mundarie siltstone" which, according to Condon (1967, p. 43), was deposited in "fairly deep water directly from icebergs derived from continental ice-sheet." Condon (1967) listed a "Calceolispongiidae,spec. nov." from the "Thambrong formation" which he described (1967, p. 49) as having formed during a "period of rapid fluctuation of icesheet advance and retreat, with the tillitic siltstone and greywacke deposited during periods of advance and the fluvioglacial quartzwacke and varves during period of retreat." Unfortunately, it is not recorded in which of these facies the calceolispongiid occurs.

The last occurrence of this family in the Lyons Group is in the Carrandibby Formation which Condon (1967) regarded as post-Lyons, but which Playford et al. (1975) and Hocking (1985) regarded as a formation at the top of the Lyons Group in the northern Carnarvon Basin. This species is said by Dickins and Thomas (1959) to be similar to one recorded from marine Permian beds in Umaria, India (see Teichert 1949 pl. 25, figs. 19-22). An unnamed calceolispongiid from the top of the Grant Group of the Canning Basin ('Calceolispongid gen. et spec. nov." of Dickins and Shah 1977) probably represents the same, or a closely related, genus. Regrettably, none of this material has ever been studied in detail. This is another glaring example of an "unpublished fossil record" to which Teichert *et al.* (1987) called attention: important fossil materials that rest for decades unattended, often poorly curated, in museums and research collections all over the world. The calceolispongiids from the Lyons Group were collected in the late 1940s and early 1950s, mostly by geologists of the Bureau of Mineral Resources, Geology and Geophysics, and, during the last 40 years, have joined untold numbers of fossils awaiting study and description in the museums of the world.

Calceolispongia is a most unusual and distinct genus of crinoids that became first known as a prolific member of the Artinskian warm-water faunas of Timor (as *Dinocrinus* Wanner 1916) and Western Australia (Teichert 1949). It now seems that the family Calceolispongiidae originated among Asselian cold-water faunas of the Lyons Group in the Carnarvon Basin and the Grant Group in the Canning Basin. It would be of considerable interest to learn how the changeover from a cold-water to a warm-water environment affected the evolution of this family.

The Callytharra Formation rests with a strong disconformity on the rocks of the Lyons Group. It has yielded the two smallest species of *Calceolispongia* known so far. The virtual absence of the genus from rocks of the Wooramel Group may be due to facies changes, because the rocks of this group are described as predominantly arenaceous (Condon 1967). No significant additions have been made to the knowledge of Calceolispongiidae in the Byro and Kennedy Groups since publication of my monographic description (Teichert 1949).

Outside the Carnarvon Basin, calceolispongiids are, in Western Australia, known from the Perth and Canning Basins, where they are much more restricted stratigraphically. The Fossil Cliff Member of the Holmwood Shale in the Perth Basin has yielded only *Calceolispongia digitata*, one of the two small species of the Callytharra Formation of the Carnarvon Basin. In the Canning Basin, only the Noonkanbah Formation and the Grant Group have yielded calceolispongiids, most of them recorded without adequate locality and stratigraphic data. They are: *Calceolispongia hindei*, *C. rotundata*, *C. rubra*, *C. spectabilis*, and *C.* sp. ind. of Guppy *et al.* (1950), in the Noonkanbah Formation; an undescribed species, probably representing a new genus, in the Grant Formation. The Noonkanbah Formation is generally regarded as the equivalent of the Byro Group of the Carnarvon Basin (see Playford et al. 1975), but from the composition of its *Calceolispongia* fauna it is clear that it represents no more than the equivalents of the Wandagee Formation and perhaps some of the Coolkilya Formation. The unidentified calceolispongiid in the Grant Group was found near the top of this unit and is of early Sakmarian age.

Palaeontology

Phylum Echinodermata

Subphylum Crinozoa Matsumoto, 1929

Class Crinoidea Miller, 1821

Subclass Inadunata Wachsmuth & Springer, 1885

Order Cladida Moore & Laudon, 1943

Suborder Poteriocrinina Jaekel, 1918

Superfamily Calceolispongiacea Teichert, 1954

Cup large to small, base concave to flat, distinguished mainly by prominent spine- or spade-like projects of basals in most species, arms five, obliqui-uniserial (Lane in Moore & Teichert 1978, p. 754).

Remarks: The family Calceolispongiidae Teichert (1954) was upgraded to superfamily status by Moore, Lane, and Strimple (in Moore & Strimple 1973). After discovery of species of *Calceolispongia* that show no significant thickening of the basals, Willink (1979) suspected that this family might just be a specialized end branch of the Texacrinacea Strimple.

Range and Distribution: Lower Permian: Australia (Western Australia, Queensland, New South Wales, Tasmania), Indonesia (Timor), India (Punjab Himalaya, Umaria). Upper Permian: Australia (Queensland, New South Wales).

Family Calceolispongiidae Teichert, 1954

Cup large, bowl-shaped, with shallow basal invagination; infrabasals small, concealed by stem, not visible from side; basals large, in most species spinose or tuberculate; radial arm facets wide, inclined outward-upward; one anal plate in cup, separating radials. Arms uniserial, unbranched, pinnulate. Stem small, relative to cup size (Lane in Moore & Teichert, 1978, p. 755).

Range and distribution: as for superfamily.

Remarks: In a discussion of the genus *Jimbacrinus*, Yakovlev (1964, p. 109-111) dismisses the features of the *skulptura* (sculpture) of the cup plates as taxonomically unimportant and states that this genus and *Calceolispongia* should not have been placed in a new family. However, he does not cite my 1949 monograph and does not discuss *Calceolispongia*. The Calceolispongiidae, as well as the Calceolispongiacea, were retained in the *Treatise on Invertebrate Paleontology* (Lane in Moore & Teichert 1978) and also by Willink (1979).

Calceolispongia Etheridge, 1915

(Synonym: *Dinocrinus* Wanner, 1916)

Type species: *Calceolispongia hindei* Etheridge, 1915.

Cup large to small, bowl-shaped, with very shallow to deep basal concavity and indented basal-radial sutures; infrabasals small, diamond-shaped, not visible or barely visible from side; basals hexagonal except for CD basal which is truncated by anal X; basals greatly thickened and expanded into large, hornlike, or spade-shaped projections, or unthickened and ornamented by tubercules or spines; radials pentagonal, shorter than basals, separated by anal X in CD interray; radial arm facets occupying full width of plates, inclined outward and upward, muscle area long. Arms unbranched, uniserial, pinnulate, coiling; proximal 2 brachials large and trapezoidal, distal brachials cuneiform. Brachial articulations predominantly muscular. Stem small, relative to cup size, circular in section, having long, slender cirri (very slightly modified after Willink 1979, p. 164).

Range and distribution: Lower Permian: Australia (Western Australia, Queensland, New South Wales), Indonesia (Timor), India (Punjab Himalaya, Umaria, though possibly a new genus). Upper Permian: Australia (Queensland, New South Wales).

Calceolispongia abundans Teichert

1949 *Calceolispongia abundans* Teichert, p. 54-59, pl. 1, figs. 2, 7, 12, 21; pl. 6, figs. 21, 22; pl. 8, fig. 2; pl. 9; pl. 10; pl. 11; pl. 12.

Types: Holotype: Western Australian Museum G. 8501; topotypes: UWA[1] 22245-22257, 22276, 22278-22281; Western Australian Museum 8430, 8433, 8440-8442, 8484, 8485, 8666-8742, 17044.

Geographic distribution: Type locality in syncline with axis 1.3 km west of Coolkilya Pool, Minilya River, Wandagee Station, Carnarvon Basin. Distribution elsewhere poorly known.

Stratigraphic range: 25 to 35 m above base of Wandagee Formation, Byro Group.

Age: Early Permian (Artinskian, late Baigendzhinian).

Calceolispongia acuminata Teichert

1949 *Calceolispongia acuminata* Teichert, p. 59-60, plate 5, figs. 8-35.

Types: Holotype UWA 21538; topotypes and other material 21539-21543; also in Commonwealth Paleontological Collections, Canberra.

Geographic distribution: Type material is from the south bank of the Minilya River, near Bulgadoo Pool, about 5 km northwest of Wandagee Homestead, Wandagee Station, Carnarvon Basin. Other localities are the south bank of Barrabiddy Creek, about 550 m west of the junction of Quail Quail Creek, Wandagee Station, and in outcrops to the south and east of Bogadi Outcamp, Byro Station, Carnarvon Basin.

Stratigraphic range: Uppermost part of Bulgadoo Shale, Byro Group, but exact range not known. Doubtfully listed from unspecified horizon of the Mallens Formation in the southern Carnarvon Basin (Dickins in Condon 1967).

Age: Early Permian (Artinskian, early Baigendzhinian).

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[1] UWA = Geology Department, University of Western Australia

Calceolispongia barrabiddiensis Teichert

1949 *Calceolispongia barrabiddiensis* Teichert, p. 60-61, pl. 3, figs. 1-7.

Types: Holotype UWA 21523; paratypes UWA 21521, 21524.

Geographic distribution: On east limb of Barrabiddy anticline, outcrops 400 to 800 m south of Barrabiddy Dam, Wandagee Station, Carnarvon Basin.

Stratigraphic Range: Shale of the Coyrie Formation (see Condon 1967 p. 131), associated with *Pseudoschistoceras simile* Teichert.

Age: Early Permian (Artinskian, early Baigendzhinian).

Calceolispongia digitata Teichert

1949 *Calceolispongia digitata* Teichert, p. 61-63, p. 2, figs. 1-45.

Types: Holotype UWA 21526; topotypes UWA 21517-21530.

Geographic distribution: Type material from about 800 m west of Callytharra Spring on One Gum Creek, 450 m upstream from its junction with the Wooramel River, Carnarvon Basin; also recorded from Fossil Cliff, on the north branch of the Irwin River, about 1.2 km upstream from its junction with the south branch, northern part of Perth Basin (Clarke et al. 1951).

Stratigraphic range: Callytharra Formation, Carnarvon Basin; Fossil Cliff Member of the Holmwood Shale, Perth Basin.

Age: Early Permian (latest Sakmarian, Sterlitamakian).

Calceolispongia elegantula Teichert

1949 *Calceolispongia elegantula* Teichert, p. 63-71, pl. 1, figs. 1, 8, 13; pl. 5, figs. 14-16; pl. 6, figs. 1-20, 23-80; pl. 8, fig. 1.

Types: Holotype UWA 22060a; topotypes UWA 22060-22077, 22078-22082, 22084-22097, 22099-22103, 22105.

Geographic Distribution: On both banks of Minilya River in N-S syncline with axis 1.3 km west of Coolkilya Pool, Minilya River, Wandagee Station, Carnarvon Basin; several localities in Mungadan and Nalbia Paddocks, Wandagee Station.

Stratigraphic range: Lowermost 25 m of Wandagee Formation, Byro Group.

Age: Early Permian (Artinskian, late Baigendzhinian).

Calceolispongia hindei Etheridge

1915 *Calceolispongia hindei* Etheridge, Jr., 1915, p. 9-13, pl. 4, figs. 1-9; pl. 7, figs. 5, 6.

Types: Lectotype 10930-1 Geological Survey of Western Australia; 4 paratypes in same collection; topotypes UAW 21465-21468, 20773, 20774.

Geographic distribution: Type locality southeast corner of Mount Marmion, close to the foot of the slope, Kimberley Downs Station, Canning Basin; also 2 localities on Wandagee Station, Carnarvon Basin.

Stratigraphic range: Near top of Noonkanbah Formation in Canning Basin; lowest beds of Coolkilya Sandstone in Carnarvon Basin.

Age: Early Permian (Roadian).

Calceolispongia multiformis Teichert

1949 *Calceolispongia multiformis* Teichert, p. 75-80, pl. 1, figs. 3, 5, 6, 10, 11, 14, 15, 17, 18, 23, 24; pl. 14; pl. 16.

Geographic distribution: Type locality in N-S syncline on Minilya River with axis 1.3 km west of Coolkilya Pool, Minilya River, Wandagee Station, Carnarvon Basin; also from a few additional localities on Wandagee Station; doubtfully identified from an unspecified locality in Noonkanbah Formation, Canning Basin; also reported from Chimlo-da-Fali and Tramavala in the Chamba syclinorium of the Punjab Himalaya, India (Kapoor 1973).

Stratigraphic range: 50-56 m above base of Wandagee Formation, Byro Group; indeterminate horizon in Noonkanbah Formation, Canning Basin; Tramavala Formation, Bhallesh Group, in the Punjab Himalaya.

Age: In Australia, Early Permian (Artinskian, late Baigendzhinian); in India, "earliest Permian" (Kapoor 1973).

Calceolispongia robusta Teichert

1949 *Calceolispongia robusta* Teichert, p. 80-83, pl. 24.

Types: Holotype UWA 21476; paratype UWA 21469.

Geographic distribution: Near SE corner of Wandagee Hill, about 800 m on N145°E of SE corner of Shed Paddock, Wandagee Station, Carnarvon Basin (for further details see Teichert 1949 p. 82).

Stratigraphic range: Coolkilya Sandstone, Kennedy Group. [Exact position in Coolkilya Sandstone unknown; the vertical range of probably 900 feet (275 m) given by Teichert (1949, p. 82) is certainly wrong, because the thickness of the formation around Wandagee Hill is stated to be only about 700 feet (213 m) (Condon 1967, p. 183). On the basis of data supplied by Dickins (1963, p. 147) the highest occurrence seems to be in the middle part of the Coolkilya Sandstone (which is about 200 m thick)].

Age: Early Permian (Roadian).

Calceolispongia rotundata Teichert

1949 *Calceolispongia rotundata* Teichert, p. 83-85, pl. 4, figs. 25-42; pl. 5, figs. 1-13.

Types: Holotype UWA 21504; paratype UWA 21505; topotypes 21506-21516, 22083, 22104, 22117-22119.

Geographic distribution: On both banks of Minilya River in N-S syncline with axis 1.3 km west of Coolkilya Pool, Minilya River, Wandagee Station, Carnarvon Basin; about 1.5 km east of Noonkanbah Homestead, Canning Basin.

Stratigraphic range: Throughout lower 50 m of Wandagee Formation, Byro Group, Carnarvon Basin; indeterminate horizon in Noonkanbah Formation, Canning Basin.

Age: Early Permian (Roadian).

Calceolispongia rubra Teichert

1949 *Calceolispongia rubra* Teichert, p. 85-89, pl. 10, figs. 11, 12; pl. 17; pl. 18, figs. 1-36, 44-47.

Types: Holotype UWA 22206; topotypes UWA 22207-22215, 22217.

Geographic distribution: In small east-west striking syncline about 500 m south of Minilya River and 800 m SE of Curdamuda Well, Wandagee Station, Carnarvon Basin; also known from other localities on Wandagee Station farther south. About 1.5 km east of Noonkanbah Homestead, Canning Basin.

Stratigraphic range: About 45-55 m above base of Wandagee Formation, Carnarvon Basin; indeterminate horizon in Noonkanbah Formation, Canning Basin.

Age: Early Permian (Artinskian, late Baigendzhinian).

Calceolispongia spectabilis Teichert

1949 *Calceolispongia spectabilis* Teichert, p. 89-92, pl. 1, fig. 9, pl. 18, figs. 37-43, 48, pl. 19; pl. 20.

Types: Holotype UWA 21519; paratypes UWA 22141a-e; topotypes UWA 22135, 22137-22140; Western Australian Museum 8486-8494; other material UWA 21517, 21518, 22136.

Geographic distribution: Syncline with N-S axis 1.3 km west of Coolkilya Pool, Minilya River, Wandagee Station, Carnarvon Basin; also in scattered localities elsewhere on Wandagee Station. Tentatively identified from unidentified locality in Noonkanbah Formation, Canning Basin.

Stratigraphic distribution: 60 to 145 m above base of Wandagee Formation, Byro Group, Carnarvon Basin. Unidentified horizon in Noonkanbah Formation, Canning Basin.

Age: Early Permian (Artinskian, late Baigendzhinian).

Calceolispongia spinosa Teichert

1949 *Calceolispongia spinosa* Teichert, p. 92-93, pl. 2, figs. 46-72.

Types: Holotype UWA 21533; paratypes and topotypes UWA 21554, 21536, (basals), 21535 (radials), 22287 (2nd brachial).

Geographic distribution: 800 m west of Callytharra Spring on One Gum Creek, 450 m upstream from its junction with the Wooramel River, Carnarvon Basin.

Stratigraphic Range: Callytharra Formation.

Age: Early Permian (latest Sakmarian, Sterlitamakian).

Calceolispongia truncata Teichert

1949 *Calceolispongia truncata* Teichert, p. 93-95, pl. 3, figs. 36-56; pl. 4, figs. 1-21.

Types: Holotype UWA 21545; topotype UWA 21546; other material 21547-21549, 21525.

Geographic distribution: Type locality on south side of Minilya River, 1 km southeast of Coolkilya Pool, Wandagee Station, Carnarvon Basin; scattered outcrops farther upstream from type locality and elsewhere on Wandagee Station.

Stratigraphic Range: About 120 m below top of Cundlego Formation, Byro Group, but vertical range not well established. In the type section, the Cundlego Formation is 332 m thick.

Age: Early Permian (Artinskian, Baigendzhinian).

Calceolispongia sp. ind. A

1949 *Calceolispongia* sp. ind. A, Teichert, p. 95-96, pl. 2, figs. 19, 20; pl. 23, figs. 13-16.

Material: UWA 21475, 21500, 21501.

Geographic distribution: In centre of syncline 1.3 km west of Coolkilya Pool, Minilya River, Wandagee Station, Carnarvon Basin; also additional scattered localities on Wandagee Station.

Stratigraphic range: Probably Nalbia Sandstone, Byro Group (associated with *Calceolispongia robusta*).

Age: Early Permian (Roadian).

Calceolispongia sp. ind. B

1949 *Calceolispongia* sp. ind. B, Teichert, p. 96, pl. 23, figs. 17-18.

Material: UWA 21498.

Geographic occurrence: Southeastern part of Wandagee Hill, Wandagee Station, Carnarvon Basin.

Stratigraphic range: Coolkilya Sandstone, Kennedy Group.

Age: Early Permian (Roadian).

Calceolispongia sp. ind. C

1949 *Calceolispongia* sp. ind. C., Teichert, p. 96, pl. 23, figs. 19-21.

Material: UWA 21499.

Geographic distribution and *stratigraphic range*: As for *Calceolispongia* sp. ind. B.

Age: Early Permian (Roadian).

Calceolispongia sp. ind. D

1949 *Calceolispongia* sp. ind. D, Teichert, p. 96-97.

Material: UWA 21502.

Geographic occurrence: Southeast limb of syncline west of Coolkilya Pool, Minilya River, Wandagee Station, Carnarvon Basin.

Stratigraphic range: Probably Baker Formation, Byro Group.

Age: Early Permian (Roadian).

Calceolispongia sp. ind. E

1949 *Calceolispongia* sp. ind. E, Teichert, p. 97, pl. 4, figs. 22-24.

Materials: UWA 215201

Geographic occurrence: Nalbia Paddock, 1800 m due east of NE corner of Mungadan Paddock, Wandagee Station, Carnarvon Basin.

Stratigraphic range: Quinnanie Shale, Byro Group.

Age: Early Permian (Artinskian, late Baigendzhinian).

Calceolispongia sp. ind. F

1949 *Calceolispongia* sp. ind. F, Teichert, p. 97, pl. 2, figs. 73-76.

Material UWA 21522.

Geographic occurrence: On east limb of Barrabiddy anticline, outcrops 400-800 m south of Barrabiddy Dam, Wandagee Station, Carnarvon Basin.

Stratigraphic range: Coyrie Formation, basal Byro Group; associated with *Calceolispongia barrabiddiensis*.

Age: Early Permian (Artinskian, early Baigendzhinian).

Calceolispongia sp. nov.

1967 *Calceolispongia* spp. nov., Dickins in Condon, p. 152.

Diagnosis: None published

Geographic distribution: Unspecified locality in southern part of Carnarvon Basin.

Stratigraphic range: Mallens Sandstone, Byro Group.

Age: Early Permian (Artinskian, early Baigendzhinian).

Calceolispongia sp.

1967 *Calceolispongia* sp., Condon, p. 35.

Diagnosis: None published

Geographic distribution: 0.6—1.25 km west of Coyango Well, Williambury Station, Carnarvon Basin (ML 6).

Stratigraphic range: Lyons Group. (This may be the oldest recorded species of Calceolispongiidae).

Age: Early Permian (Asselian).

Calceolispongia sp.

1967 *Calceolispongia* sp., Condon, p. 42.

Diagnosis: None published.

Geographic distribution: Northeastern corner of Mundarie Paddock, Middalya Station, Carnarvon Basin (MG 158).

Stratigraphic range: Lyons Group.

Age: Early Permian (Asselian).

Calceolispongia sp.

1967 *Calceolispongia*, Condon, p. 97.

Diagnosis: None published; cup and brachials reported.

Geographic distribution: 7.25 km west of Moogooree Homestead and 800 m north of road from Moogooree to Donellys Well, Carnarvon Basin (TP 323).

Stratigraphic range: Upper part of Billidee Formation, top of Wooramel Group.

Age: Early Permian (Artinskian, early Baigendzhinian).

Calceolispongia sp.

1967 *Calceolispongia*, Condon, p. 136.

Diagnosis: None published.

Geographic distribution: Unspecified locality, Carnarvon Basin.

Stratigraphic range: Mallens Sandstone, Byro Group.

Age: Early Permian (Artinskian, early Baigendzhinian).

Calceolispongia sp.

1967 *Calceolispongia* sp. Condon, p. 165.

Diagnosis: None published.

Geographic distribution: Unspecified locality in Carnarvon Basin, probably on Wandagee Station.

Stratigraphic range: Quinnanie Shale, Byro Group.

Age: Early Permian (Artinskian, late Baigendzhinian).

Calceolispongia sp.

1967 *Calceolispongia*, Condon, p. 173.

Diagnosis: None published.

Geographic occurrence: Unspecified locality on either Williambury, Middalya, or Wandagee Stations, Carnarvon Basin.

Stratigraphic range: Nalbia Sandstone, Byro Group.

Age: Early Permian (Roadian).

Calceolispongia sp. ind.

1950 *Calceolispongia* sp. ind. Guppy, Cuthbert & Lindner, p. 8, pl. 1, figs. 1-3.

Diagnosis: None published.

Geographic distribution: Northern flank of Nerrima Dome, Nerrima Station, Canning Basin (145 km southeast of Derby) (Sample N17).

Stratigraphic range: Unspecified horizon in Noonkanbah Formation.

Age: Early Permian (Artinskian, Baigendzhinian).

Jimbacrinus Teichert

Type species: *Jimbacrinus bostocki* Teichert, 1954

Diagnosis: Cup large bowl-shaped with shallow invagination below; basals very large, hexagonal, mammillate; radials pentagonal, equal, smaller than basals, separated in CD interray by anal X, radial arm facets form entire upper surface of plates, inclined outward-upward; anal X quadrangular, height equal to lateral radial facets. Individual cup plates commonly ornamented with one or more tubercles. Arms uniserial, pinnulate coiling, primibrachs 1 and 2 trapezoidal, distal brachials cuneiform. Stem small relative to cup size with alternating long and short columnals (modified after Lane in Moore & Teichert 1978 by Willink 1979, p. 181).

Remarks: Yakovlev (1964, p. 109-111) discussed *Jimbacrinus* and pointed out its similarity to *Cromyocrinus*, known from the Carboniferous and Permian of Oklahoma, Arkansas, and the Moscow Basin, and suggested transfer of *Jimbacrinus* to Cromyocrinidae, regarding the differences in morphology of the basal plates as taxonomically unimportant. However, Moore, Strimple and Lane (in Moore & Teichert 1978, p. T155) retained Teichert's systematic arrangement.

Range and distribution: Lower Permian (Artinskian) of Western Australia and Tasmania.

Jimbacrinus bostocki Teichert

1954 *Jimbacrinus bostocki* Teichert, p. 71-75, pl. 13, figs. 1-7; pl. 14, figs. 1-11.

Types: Holotype BMR[1] 326; paratypes BMR 327, 329; hypotypes BMR 330-334; additional material BMR F. 17,586.

Geographic distribution: South side of Gascoyne River, 3.5 km east of Jimba Jimba Homestead, Jimba Jimba Station, Carnarvon Basin.

Stratigraphic range: Unspecified horizon in Cundlego Formation, Byro Group.

Age: Early Permian (Artinskian, Baigendzhinian).

Jimbacrinus minilyaensis Webster

1990 *Jimbacrinus minilyaensis* Webster, p. 70-71, pl. 3, figs. 2, 3.

Types: Holotype UWA 83,763; paratype UWA 83,764.

Geographic distribution: Northeast side of syncline 1.3 km west of Coolkilya Pool (*not* east of Coolkilya Pool as stated by Webster 1990).

Stratigraphic range: Unspecified horizon in Wandagee Formation.

Age: Early Permian (Artinskian, late Baigendzhinian).

Calceolispongiidae gen. nov., sp. nov.

1956 Calceolispongidae sp. nov., Dickins and Thomas, p. 126.

Diagnosis: Closely allied to calceolispongiid plates from the Umaria beds [India], described by Reed (1928) as dermal tubercles of fish" (Dickins and Thomas, 1956). Probably based on same material as "Calceolispongidae gen. et spec. nov." of Dickins and Thomas (1959). Some of the plates described by Reed (1928) were refigured by Teichert (1949 pl. 25, figs. 19-22). Nothing like these plates has ever been described from anywhere in Western Australia.

Geographic occurrence: Unspecified locality (or localities) in southern half of Carnarvon Basin.

Stratigraphic range: Unspecified horizon in Lyons Group.

Age: Early Permian (Asselian).

Calceolispongiidae gen. nov., sp. nov.

1959 Calceolispongidae gen. et sp. nov., Dickins and Thomas, p. 78.

1967 Calceolispongidae gen. et sp. nov., Condon, p. 61.

Diagnosis: None published; cup plates and columnals reported. Said to be "very close to or identical with" *Calceolispongia* sp. from Umaria, India (Dickins and Shah 1977 p. 9).

Geographic distribution: South side of Wooramel River, 800-2 400 m west of Callytharra Spring, Carnarvon Basin; also in Lyndon River area.

Stratigraphic range: Type Carrandibby Formation, uppermost Lyons Group.

Age: Early Permian (late Sakmarian).

Calceolispongiidae gen. nov.?, sp. nov.

1977 Calceolispongidae gen. et sp. nov., Dickins, Towner & Crowe, p. 277, pl. 1, fig. 1-3

Diagnosis: None published, but the illustrations show a second brachial plate, 12 mm wide, with a prominent central elevation which is 11 mm high. Said to be similar to second brachial plates described by Dickins and Thomas (1959) from the Lyons Group of the Carnarvon Basin.

Geographic distribution: Northwestern part of St. George Range, Canning Basin (BMR Locality N1206).

Stratigraphic range: Grant Group, Millajiddee Member of the Carolyn Formation.

Age: Early Permian (latest Asselian or earliest Sakmarian).

Calceolispongiidae gen. ind., sp. nov.

1967 Calceolispongidae sp. nov., Condon, p. 48.

Diagnosis: None published.

Geographic distribution: Right bank of Kialawibri Creek 2.4—3.6 km upstream from its junction with the Lyndon River, Carnarvon Basin.

Stratigraphic range: Unspecified horizon in Lyons Group.

Age: Early Permian (Asselian).

Calceolispongiidae gen. et sp. ind.

1987 Calceolispongidae sp., Webster p. 127, Fig. 15A, B.

Description: see Webster (1987).

Geographic distribution: Right bank of Kialawibri Creek 2.4—3.6 km upstream from its junction with the Lyndon River, Carnarvon Basin.

Stratigraphic range: Unspecified horizon in Thambrong Formation, Lyons Group.

Age: Early Permian (late Sakmarian).

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[1] BMR = Bureau of Mineral Resources, Geology and Geophysics, Canberra

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An account of the decline of Lake Towerrinning, a wheatbelt wetland

R H Froend & A J McComb
Environmental Science, Murdoch University, Murdoch, WA 6150

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Abstract

Lake Towerrinning, a wetland in the wheatbelt of Western Australia, is valued for both recreation and conservation. Water quality, however, has decreased dramatically in recent years, threatening its value for water sports and as a waterbird refuge. A preliminary investigation of water quality and vegetation decline was conducted to determine the sequence of events that led to the current levels of degradation. Turbidity, salinity, and water nutrients were found to be very high. Reduced stabilization of the sediment due to the demise of the fringing rush vegetation, and algal blooms caused by nutrient-rich runoff from agricultural land, were seen to be the major contributors to high turbidity. The decline in the fringing rush (around the lake) and tree vegetation (around lake and within the catchment) due to clearing and increased salinity is thought to be the turning-point in the sequence of events which lead to a reduction in water quality.

Introduction

Lake Towerrinning, situated 32 km south of Darkan (lat. 33°20′, long. 116°44′), is typical of degraded wetlands in the wheatbelt of Western Australia. Catchment clearing has resulted in the mobilization of salts from subsurface soils and eventual salinization of what was once a freshwater lake. Although secondary salinity has been well recorded for the Wheatbelt (Burvill 1950; Conacher and Murray 1973; Henschke 1980), there is little documentation of its effects on wetland ecosystems. Lake Toolibin is an exception where monitoring programs and research have been conducted since 1977; this has provided a valuable case history for the gradual decline of a wetland habitat and associated flora and fauna due to secondary salinity (Mattiske, 1978; Froend *et al.* 1987; Halse 1987; NARWRC, 1987; Bell & Froend, 1990). The Toolibin studies emphasised the importance of historical information and monitoring in determining the sequence of events which lead to environmental change and degradation.

Unlike Lake Toolibin, Lake Towerrinning (Fig. 1) is a permanent lake with a long history of recreational activity such as picnicking, swimming, sailing, and water skiing. Because it contains water permanently, it is also of critical importance as a drought refuge for waterbirds (Jaensch 1988). However, there has been a pronounced decline in the fringing rush and tree vegetation which is vital for waterbird habitat. The West Arthur Shire and the Department of Conservation and Land Management (CALM) expressed concern over the decline in water quality of the lake since 1973, and whether or not the present level of boating activity is having an adverse effect on the lake, its waterbirds, turbidity and marginal vegetation. A gradual increase in salinity, turbidity, and odour threatens the future of the lake both as a waterbird refuge and recreation area.

This study aimed to describe the sequence of events which led to the degradation of Lake Towerrinning, and deduce the mechanisms of this degradation through a quantitative assessment of current water quality.

Methods

Records for salinity and lake levels have been collected at bimonthly intervals as part of the South West Wetland Monitoring Program conducted by J Lane and D Munro of CALM, since November 1979. Maps of the fringing vegetation and estimates of rate of vegetation decline were also provided by CALM. Historical information regarding the use of the lake and catchment was provided by the West Arthur Shire.

Field investigations were limited to two days (26 July, 20 September, 1986) concentrating on salinity and turbidity aspects. Eight sampling sites were located around the lake on a grid pattern (Fig. 1). At sites 1, 3, 6, and 8 water samples were taken at intermediate depth and analysed for concentration of total phosphorus, ammonia, nitrate-nitrite, organic nitrogen, total nitrogen, and total suspended solids (inorganic and organic components) using standard techniques. At each site Secchi depth was measured and light attenuation measured with a Licor Li-186B integrated quantum photometer. Salinity and temperature were measured with a Yeo-Cal Electronics salinity/temperature meter, and a known quantity of water filtered through Whatman GF/C filter paper to extract phytoplankton for chlorophyll *a* analysis and total suspended solids. Bathymetry was determined by measuring water depth along the grid lines (Fig. 1) at approximately 50m intervals using a weighted, graduated rope.

Results

Clearing of the Catchment, Lake Levels and Salinity

Personal communication with West Arthur Shire councillors and landowners has provided historical information regarding water quality decline. More than 90% of the catchment of Lake Towerrinning has been cleared, the last major removal of native vegetation being carried out in about 1970. The lake was still considered fresh in 1966 but estimates suggest it became saline during the early 1960s. Vegetation surrounding the lake declined rapidly in the years 1966-1972. Obvious decline in the water quality has been noticed since 1973. During the last ten years, many bores sunk in the catchment have returned saline water, and the water in many dams has also become saline.

Salinity varies with lake level, due to the concentrating effects of evaporation (Fig. 2). During the drought years of 1979-81 lake levels were low and salinity levels correspondingly very high. Unseasonal rains in January 1982, caused by cyclonic activity, ended the dry weather pattern and lake levels have since remained above 2.0 m. There are many dead tree stumps submerged in the lake, some of which had to be removed for boating safety in certain areas (Shire councillors pers. comm.); this indicates that lake levels have increased over the years.

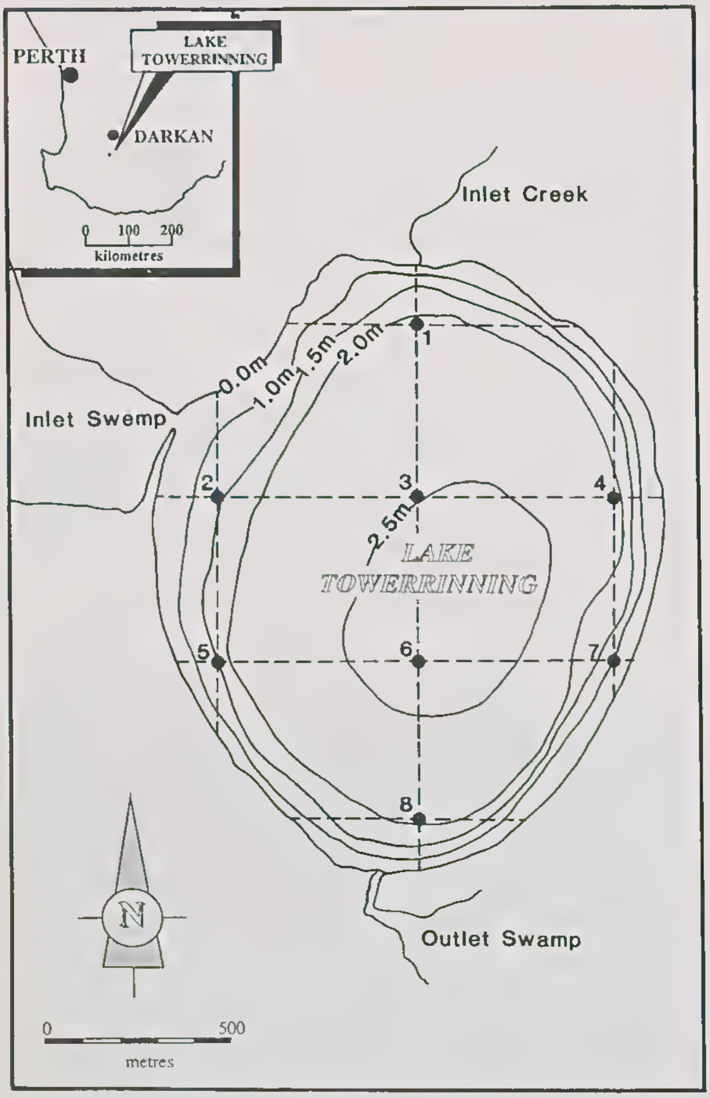

Figure 1 Lake Towerrinning showing location, sampling sites (1-8), and lake bathymetry (in metres).

Having determined the bathymetry (Fig. 1), it is possible to calculate the total salt load of the lake water from the lake level and water salinity data. Figure 3 shows changes in salt load during 1981-1986. Values during the dry period of 1979 - May 1981 are very high and are likely to be exaggerated due to the very low water levels (< 0.5 m) and consequent inaccuracy of volume determinations; these have not been included in the figure. The trend in salt load since January 1981 shows increasing amounts of salt stored in the lake until significant rainfall and subsequent outflow events occur; for example, from January 1981 to early January 1982 salt load increased to 28 200 t but decreased to 13 860 t in March 1982 after the lake overflowed from cyclonic rainfall. This trend continues up to July 1983 (28 300 t) until heavy rainfall and subsequent outflow again reduced the salt load in September 1983 (22 930 t). It is likely that continued input of saline surface and groundwater adds to the salt load during years of no outflow. Apart from these events, the salt load of the lake is increasing by approximately 6500 t per year.

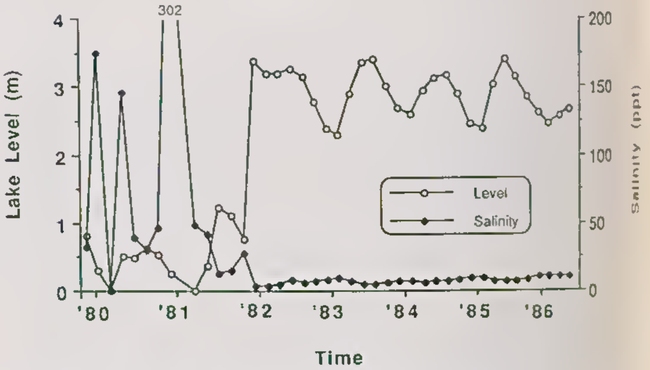

Figure 2 Lake level and salinity measurements taken at bimonthly intervals from November 1979 to September 1986 at Lake Towerrinning.

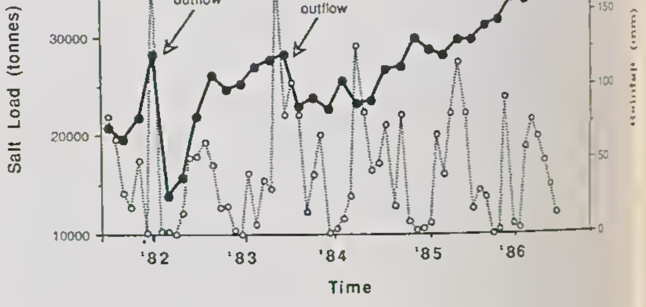

Figure 3 Total salt load for the period July 1981 to September 1986 at Lake Towerrinning. Outflows occurred during January 1982 and July - August 1983.

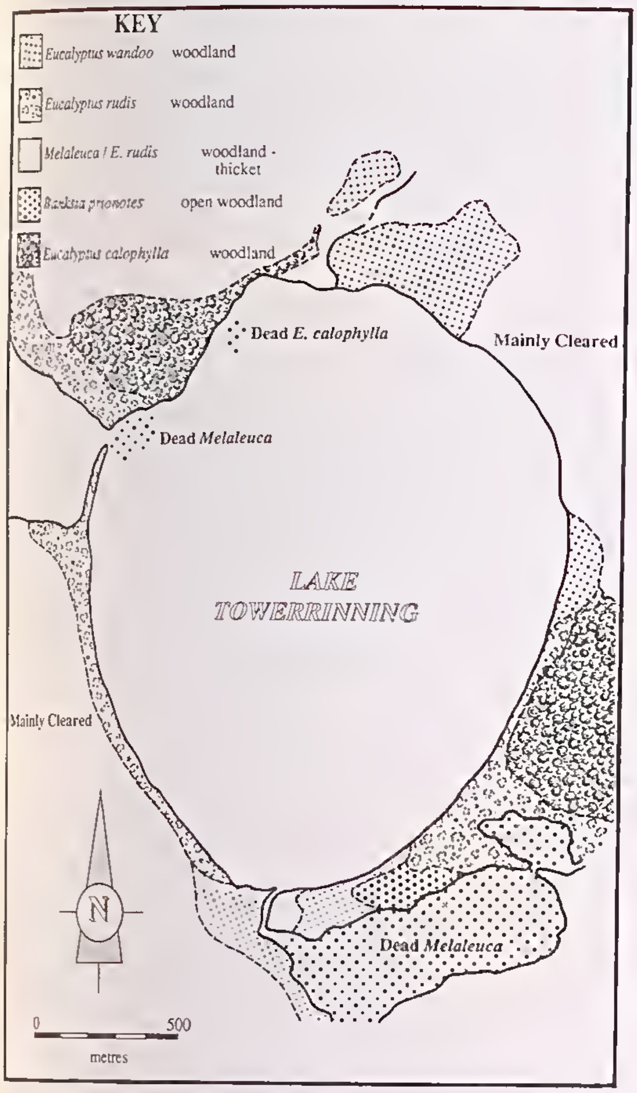
KEY
Eucalyptus wandoo woodland
Eucalyptus rudis woodland
Melaleuca / E. rudis woodland - thicket
Banksia prionotes open woodland
Eucalyptus calophylla woodland
Dead E. calophylla
Mainly Cleared
Dead Melaleuca
LAKE TOWERRINNING
Mainly Cleared
N
Dead Melaleuca
0
500
metres

Figure 4 Vegetation formations surrounding Lake Towerrinning. Mapped during 1985 and provided by CALM.

Loss of wetland vegetation

Clearing for agriculture has left a narrow peripheral band of vegetation 100—400 m wide. This peripheral vegetation has been severely affected by increasing soil salinity and flooding. Adjoining landowners noticed that most of the tree vegetation of the inlet swamp (Fig. 4) was dead by 1973, and that decline in tree vigour commenced during the early 1960's.

The vegetation surrounding the lake was mapped in 1985 by CALM (Fig. 4). Almost all of the remaining *Eucalyptus wandoo* and *E. rudis* woodlands to the north have no understorey. Stock have access to the north-east, south-west and southern perimeter of the lake, and the understorey there is heavily disturbed and limited to introduced weeds and grasses. Woodlands to the south-east are more extensive and protected from grazing, and have a more intact understorey. Partially-submerged dead *Melaleuca rhaphiophylla* and *E. calophylla* at the north-west perimeter of the lake indicate increased lake levels and salinity. *Melaleuca / E. rudis* woodland is the main vegetation type at or near both lake inlet and overflow and along the overflow route to Arthur River. The woodland is in varying states of degradation. Most of the *M. rhaphiophylla* in the lake overflow is dead, and weed invasion and heavily-grazed native understorey is seen in most unreserved areas.

Mapping of the distribution of *Baumea articulata* by aerial photograph interpretation (Fig. 5) shows the rush vegetation has dramatically declined since 1964. Virtually all the *Baumea articulata* had died by 1973 and by 1985 only about a dozen small (1-4 m^2) remnants remained. Both local farmers and CALM officers have commented on the presence of a benthic "carpet" of aquatic plants on the lake bed before the late 1970s. The "carpet" occurred throughout the deeper portions of the lake, always beneath mean lake level, but was lost when the lake substantially dried-out during the drought years, probably between 1979-81.

Water quality assessment

The Secchi disc transparency depths averaged 0.5 m with negligible variation between sites, and the mean attenuation coefficient was 0.60. These results show relatively poor light penetration attributed to high water turbidity.

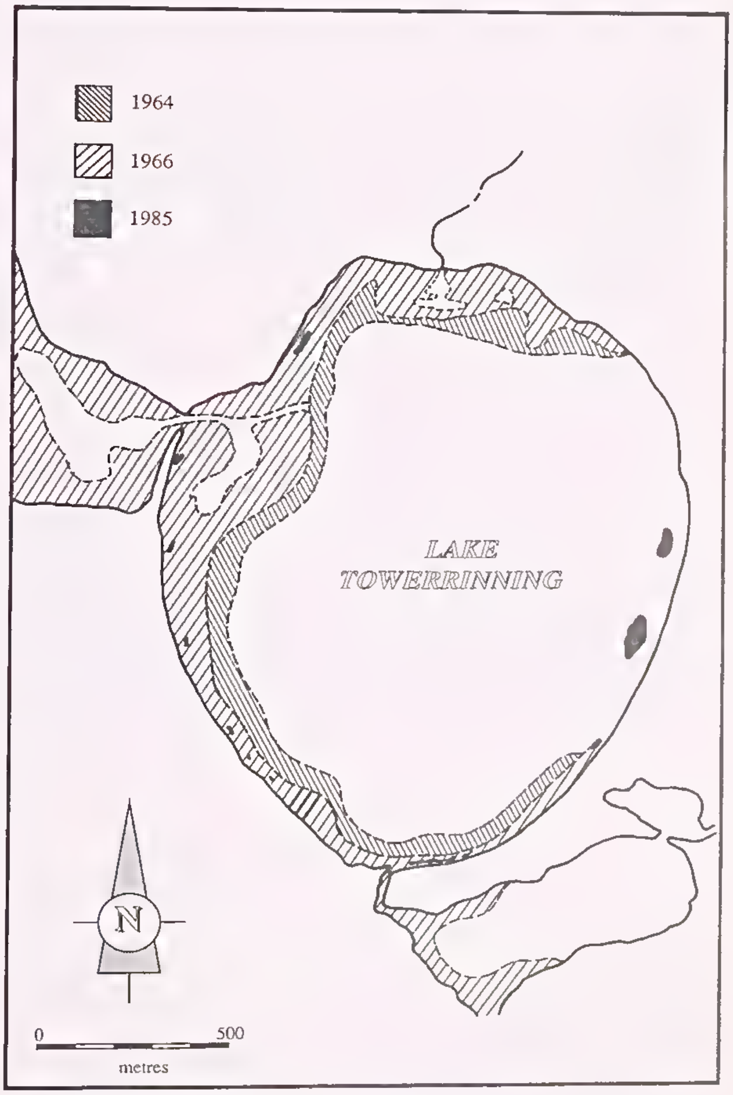

Figure 5 Distribution of *Baumea articulata* at Lake Towerrinning during 1964, 1966, and 1985.

Table 1

Inorganic, organic component of total suspended solids (TSS) and chlorophyll *a* concentrations of Lake Towerrinning. Data collected on 26 July 1986

Site	Inorg.Solids mg/L	Org.Solids mg/L	TSS mg/L	Chlorophyll *a* µg/L
1	21.6	54.4	76.0	37.4
2	—	—	—	48.1
3	13.0	15.8	28.8	48.2
4	17.0	50.8	67.8	42.7
5	8.0	46.8	54.8	42.8
6	6.0	12.8	18.8	48.1
7	37.4	56.4	93.8	42.7
8	3.6	8.2	11.8	26.7
Mean	15.2	35.0	50.3	42.1

The lake had a uniform salinity of 10 parts per thousand (ppt) with no detectable change with depth. This value is high for winter; Lake Towerrinning can be considered brackish during winter and saline-hypersaline during the drier summer months. Water temperature was constant at 12°C, with no stratification.

Both the organic and inorganic components of total suspended solids (TSS) and chlorophyll *a* levels are shown in Table 1. A high proportion of organic solids was present in the water column, and could be accounted for by high levels of suspended detritus and/or the high levels of algae as indicated by the chlorophyll *a* concentrations. In general the suspended solids were not high, but turbidity can be attributed to the high concentrations of chlorophyll *a* obtained. This indicates that an algal bloom was occurring at the lake. Differences in TSS between sites could be attributed to water turbulence increasing the suspension of sediment/detritus in shallow water close to the shore (sites 1, 4, 5, 7, and 8). Chlorophyll *a* concentrations showed negligible variation between sites.

Results of the nutrient analyses performed on the water samples collected are shown in Table 2. Total phosphorus levels were very high but inorganic nitrogen concentrations were low. This is attributed to the high proportion of organic nitrogen, indicating that most of the nitrogen entering the lake is taken up by algae in the water column. Total nitrogen concentrations are significantly higher during September. This is primarily due to higher organic nitrogen and, to a lesser extent, ammonia concentrations. The algal bloom observed in July was chiefly comprised of a species of *Anacystis*, a blue-green algae able to fix atmospheric nitrogen. This may account for the increase in both organic nitrogen and ammonia during September when higher temperatures and longer light periods promote increased rates of algal reproduction and metabolism. Although chlorophyll *a* concentrations were not determined in September, it was observed that the algal bloom was still occurring.

Discussion

The mechanisms which brought about the decrease in water quality can be deduced from the historical information and records of the lake and its catchment. The reduction in fringing vegetation of the lake (and catchment) is a milestone in the series of events leading to poor water quality. The reasons for the decline in vegetation could be increased flooding or salinity. Fringing rush and tree vegetation requires a particular inundation regime and if the depth and duration of inundation are increased vegetation of lower elevations may die and the margin will retreat to a higher elevation of suitable inundation regime. If the change in inundation is rapid and combined with increasing salinity, then the result may be local extinction rather than changes in distribution. Although increased surface water (and probably groundwater) input from the catchment due to clearing may be responsible for the initial decline of the fringing vegetation, increasing salinities would have severly limited recruitment. *Baumea articulata* is adapted to freshwater conditions and has a low tolerance to saline water, and so the salinity of Lake Towerrinning is considered the major cause of the decline and failure of re-establishment of the fringing sedges. The drought period during the late 1970s and early 1980s would have compounded the problem because of high soil surface salinities. Data indicate that outflow events significantly reduce the salt load of the lake, implying that artificially increasing outflow frequency and controlling lake levels is a means of reducing water salinity.

It is possible that a large proportion of the suspended organic matter is derived from the comparatively sudden senescence and decomposition of the fringing *Baumea articulata* due to the increase in salinity; this would have caused the following problems:

a) An increase in the detritus input to the water column and sediment due to decomposing plant material, causing an increase in the nutrient load and turbidity.

Table 2

Water nutrient concentrations of Lake Towerrinning on 26 July (JUL) and 20 September (SEP)

Site	Total P µg/L JUL	Total P µg/L SEP	Ammonia µg/L JUL	Ammonia µg/L SEP	Nitrate-Nitrite µg/L JUL	Nitrate-Nitrite µg/L SEP	Organic N µg/L JUL	Organic N µg/L SEP	Total N µg/L JUL	Total N µg/L SEP
1	73	86	54	89	14	6	373	2091	442	2186
3	73	84	58	100	10	5	482	2119	549	2224
6	72	69	57	103	10	7	994	1494	1061	1604
8	72	79	83	97	11	8	835	1966	929	2071
Mean	72.5	79.5	63	97.2	11.2	6.5	671	1917.5	745.2	2021.2

Table 3

Comparison of Lake Towerrinning nutrient levels, Secchi depth and chlorophyll levels with some Western Australian freshwater lakes

	Total P µg/l	Inorganic N µg/l	Secchi depth m	Chlorophyll *a* µg/l	Trophic Class (Rast and Holland, 1988) P	Chl *a*
Loch McNess	13	220	100%[1]	0.44	Meso.	Ultra Oligo.
Lake Monger	49	440	100%[1]	1.54	Eutro.	Oligo.
Lake Joondalup	44	890	0.8	3.94	Eutro.	Meso.
Lake Towerrinning	72	74	0.5	42.02	Eutro.	Eutro.

[1]: Secchi depth exceeds lake depth.

b) A reduced or absent fringing vegetation permitting greater amounts of nutrients from the surrounding pasture (and catchment) to enter the lake water and sediments.

c) A reduction in the stabilizing effect of rushes on the sediment; in the absence of rushes the sediment can be disturbed and re-suspended in the water column, causing turbidity and increased nutrient load of the water.

d) Increased wind mixing due to a reduction in the sheltering effect of fringing rush vegetation causing suspension of particulate matter.

The rush and tree vegetation is also an important habitat for waterbirds, and loss of this habitat must have considerably altered the potential of the lake for supporting bird populations. Increased water salinities will also affect submerged macrophytes, phytoplankton, and macroinvertebrate fauna, a further limitation on waterbird habitat. Regrowth of the benthic 'carpet' since the drying of the lake would have been restricted due to higher salinity and turbidity, adding to the destabilization of the sediment.

As indicated by the total suspended solids and chlorophyll *a* results, both living and dead particulate matter contribute to the turbidity. Although the high proportion of organic solids suggests large amounts of organic particulate matter in suspension, a large percentage of the suspended organic matter would be phytoplankton. The total suspended solids levels would account for the low Secchi depths obtained. Even at low windspeed, mixing of the water column occurs due to the shallow depth of the lake and large fetch, which is supported by the lack of salinity and temperature stratification. It is likely therefore that wind mixing rather than occasional use of power boats is responsible for the maintenance of turbidity..

High total phosphorus concentrations indicate that nutrient-rich runoff from the surrounding agricultural land has led to increased primary productivity. Input of nutrients from the surrounding land could be in the form of nitrate from legume pastures and phosphate from applied fertilizers. A high proportion of the nitrogen is organic, suggesting that nitrate entering the system is rapidly consumed by phytoplankton, or that the suspended organic particulate matter is rich in nitrogen. The former explanation is supported by the high chlorophyll *a* concentrations. Increased nutrients may also be due to input from the death and decomposition of fringing rush vegetation. Removal of the rush vegetation may have also resulted in the re-suspension of nutrients stored in the sediments.

Although field sampling for water quality was limited, an indication of trophic status can be deduced. A comparison of Lake Towerrinning with freshwater lakes in Western Australia whose trophic status has been documented more extensively (Gordon *et al* 1981; Table 3) shows that Lake Towerrinning has much greater phosphorus and chlorophyll *a* concentrations, suggesting a comparatively advanced state of eutrophication. Turbidity of Lake Towerrinning is also greater than Lake Joondalup, as indicated by the shallow Secchi depth. When the classification of trophic status by Rast and Holland (1988) is applied, Lake Towerrinning is classified as eutrophic based on total phosphorus and chlorophyll *a* (Table 3). If the trophic probability classification scheme based only on chlorophyll *a* concentration is applied (Rast and Holland, 1988), Lake Towerrinning is classed as hypertrophic. However, it should be emphasised that these comparisons are not based on annual average chlorophyll *a* and nutrient concentrations, as for the other lakes used for comparison.

In conclusion, increased inputs of water, salt and nutrients from the cleared agricultural land within the lake catchment have resulted in a decline in the wetland vegetation and an increase in phytoplankton. Algal blooms and the destabilisation of the sediment are the major causes of the high turbidity currently experienced.

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